A FEEDBACK DYNAMICS ANALYSIS OF SECONDARY CONTROL OF A PRIMARY FLOW STREAM

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A FEEDBACK DYNAMICS ANALYSIS OF

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SUMMARY

This thesis examines the dynamic characteristics of a structured primary/secondary control model relative to parameter adjustments and relates the model to real managerial environments. It exemplifies the integration of frequency, time, and statistical analyses as tools of a feedback dynamics methodology, utilized here for the analysis of a linear feedback control system. The concept of control of a primary flowstream by a secondary sector recognizes the inability to directly change the inflow to a primary sector without first changing the level of the secondary sector. The system's analysis focuses upon the oscillatory characteristics of the system and determines the dominance of certain model parameters in controlling the model's responses to transient inputs. The management policies regarding time horizons for system monitoring and adjustment times for the correction of system errors coupled to an organizations goals and means for system adjustment determine the characteristics of the oscillatory response of the control system. This oscillatory response has a direct impact upon the financial characteristics of the system. The dominant control loop is the primary control loop with the smallest ratio between the adjustment time and the total loop delay. In the context of a production model, the concept of systems control shifts from an inventory control model to a production throughput control model depending upon the magnitudes of the two primary loop ratios. A patient managerial policy with respect to the dominant primary control loop will improve the overall system damping characteristics and decrease the excursions within the secondary sector. The responsiveness of the managerial policies of the secondary sector strongly influence the magnitudes of the excursions within the primary and secondary sectors. This integrated analysis methodology emphasizes the abilities to alter the system's overall response by altering the magnitudes of the various time related management policies within the system.

CHAPTER I

INTRODUCTION

Most organizations experience substantial fluctuations in their inventories, employment levels, order backlogs, capital funds, sales, customers, and profits. Often the deviations in these areas are attributed to exogenous inputs including market, raw material supply, labor, and monetary conditions. However, previous managerial decisions coupled with the internal dynamics of the organization may be responsible for undesirable conditions and the lack of preparedness of the system to handle external disturbances. Considering information and response delays, previous decisions may be far enough removed from present problems that they go undetected as prime causal agents of existing system conditions and system's oscillatory responses. Without a clear understanding of the dynamics of a manager's decisions, the manager is often doomed to repeat an unrecognized mistake forcing continued oscillations and amplifications of external disturbances within his or her organization.

In this thesis there is a systematic examination of a common managerial control situation which illustrates the strong ability of a system to oscillate because of internal system dynamics rather than variable exogenous inputs. A feedback dynamics analysis has been applied to the modeled control system in order to understand the system's regions of stability and the system parameters that define and influence these design regions. The system examined involves the control of a primary accumulation and associated flow streams through the control of a secondary accumulation. This control system is typical but not restricted to a portion of the control system of a production line and finished product inventory (primary sector) controlled by the size of the labor force (secondary sector). The model represents only the fundamental causal relationships of a primary/secondary control system easily enabling the model to be expanded or even restructured to a specific situation without drastically altering the conclusions regarding parameter influence and system stability.

This thesis examines not only the dynamic characteristics of a primary/secondary control model but also exemplifies the integration of frequency, time, and statistical analyses as tools of a feedback dynamics methodology for the analysis of complex nonlinear systems. This integrated methodology involves the use of the DYNAMO-compiler as a tool for time analysis of the system, the SPSS-compiler for the statistical analysis of the DYNAMO output data to determine parameter dominance, and the use of the DYNAMO-compiler and numerical solution techniques to complete a frequency analysis of the model. With regard to the analysis techniques, there is evidence that this integrated analysis methodology is substantially more powerful than any one of these techniques used alone. A survey of the possible extensions and alterations to this model indicates that it is a valuable component of the manager's decision environment with considerable room for further study.

1. "primary/secondary control" defined in "Primary and Secondary Control of Accumulations", by W. R. Fey in Proceedings for the Fourth Annual Meeting of the Southeast Region of the American Institute for Decision Sciences, Feb. 1974.

CHAPTER II

DESCRIPTION OF THE PROBLEM

There are certain characteristics of the management environment that are related to the dynamic behaviors of the system the manager seeks to organize and control. Most managers observe substantial fluctuations in their area of influence. They may attribute these fluctuations simply to exogenous conditions rather than relate them to internal responses to prior system adjustments. In a production system the impact of these fluctuations might be felt by the increased cost in training new personnel or in employee overtime, or felt by the reduction in employee productivity or the necessity for layoffs of personnel. Without an understanding of the managerial dynamics of managing a particular system, the manager, according to Mintzberg (17), remains in a decision environment that is characterized by brevity, interruption, fragmentation, and fluctuation in which the chief hazard is the superficial treatment of all problems; and according to Forrester (5), a prime result is the amplification of external disturbances throughout the management system.

To better understand the causal relationships within organizations, this thesis examines one management control system that commonly is seen in organizational structures and applies a feedback dynamics analysis methodology to this control structure. The examination of this feedback control model includes asking what response characteristics can be anticipated from this specific control structure and how specific managerial attitudes affect the dynamic responses of such a system. With the understanding of what system responses can be anticipated from a control structure, the manager is more capable of evaluating system alternatives when his or her organization experiences exogenous disturbances.

The systematic examination of a primary/secondary control structure demonstrates the strong ability of a system to oscillate because of internal system structure rather than variable exogenous inputs. In describing a management control system in the context of a servomechanical system, Beer (1) stated:

> The point about any servomechanical system is that, when it is disturbed, it goes into an oscillation of which the behavior can be measured. Basically, one of three things may happen. Either the oscillation will be amplified by the servomechanism, so that stock fluctuations grow ever more wild; or the oscillation may simply be perpetuated, so that no one is ever quite sure what is happening; or the oscillation may be damped -- finally to disappear. This admirable outcome does not happen by chance: it is fully determined by the design of the servomechanical control. If, then, the model suceeds in identifying a set of communication and decision rules across the network which conform to the laws of servomechanics, the queues and stocks and inventories can be quaranteed to be self regulating (p. 215).

Beer also points out, "If managerial systems were not basically self-regulating, it would never be possible to manage them. They would generate too much variety for us to cope with. The task of management is to do things to the system which will achieve particular results, such as making a higher profit" (p. 418).

A feedback dynamics analysis offers a methodology to examine a servomechanical type control system. Forrester (5) refers to this methodology as industrial dynamics and describes it as:

> the study of the information-feedback characteristics of industrial activity to show how organizational structure, amplification (in policies), and time delays (in decisions

> and interactions) interact to influence the success of the enterprise. It treats the interaction between flows of information, money, orders, materials, personnel, and capital equipment in a company, an industry, or a national economy (p. 13).

This experimental approach enables the analyst to simmulate the effects adjustments in management policies have upon the overall response of the control system.

Primary/Secondary Control

The concept of control of a primary flowstream by a secondary sector involves the inability of directly changing the inflow to a primary sector without first changing the level of the secondary sector. A primary/secondary control system with its increased number of system delays will respond more slowly to system pressures and have a greater tendency to oscillate around a desired system level as compared to a system of direct primary control. This system involving the indirect approach to primary control is often unavoidable unless additional control loops are able to influence productivity or conversion parameters between the two sectors.

The primary secondary control model is a managerial component control model. Mintzberg (17) stresses the need to understand the different component control models of a management environment to better understand the control points within the environment and their effects upon the system. The primary/secondary control model has many different control applications. A component model of this type was first investigated in the work of Fey and Low (8,14), in which the interactions between the industrial capacity, production level, unit orders, and unit inventories were examined to emphasize that not all oscillations within a system are caused by conditions external to the direct control of the managers within the system. "Oscillations can be generated in feedback loops which over-correct first in one direction and then in the other a variable being controlled" (8,p. 8). Further investigations into certain responses of a simplified component control system were described by Fey (9) at which time the general control system was first described as a primary/secondary control model. The emphasis of this study was upon the importance of the responsiveness of a manager to an error within the primary/secondary control system and the pursuant dynamic response of the system.

Primary/secondary control systems are an important class of control structures that exist in many environments. In this thesis the control structure will be described in the context of a simple production system. However, the control system is not restricted to production and inventory operations, but is typical of many primary/secondary control systems. Other applications of primary/secondary control would involve different flow structures, different system delays, and different productivity or conversion factors between the sectors. But each primary/secondary control structure would involve the management activities of monitoring the primary sector and determining state errors, directing adjustments in the desired state of the secondary sector, monitoring the secondary sector and determining state errors as compared to the desired secondary level, directing adjustments in the state of the secondary level, and thereby altering the controlled flow into or out of the primary sector. Therefore, while the model structure might be different for each application of primary/secondary control, the managerial functions of delayed system monitoring and adjusting are conceptually the same. In describing primary/secondary control in the production context, the structure of the system is fixed; however, the managerial functions that are common to all primary/secondary control structures and the various parameter design regions are able to be examined to develop general assumptions about the effects of various management policies upon the dynamic responses of the primary/secondary control system.

Secondary control of a primary flow stream exists in many management environments in addition to the production context focused upon in this thesis. The control of a cash flow and bank balance (primary sector) through changes in the level of revenue generating capital assets (secondary sector) is an example of the inability to alter primary flows without first changing secondary accumulation levels. If the system parameter values (parameter design region) of the examined model were appropriately altered, the model could as easily represent a skilled labor training and placement system (primary sector) controlled by the capacity of the training facilities or the number of teachers (secondary sector). The system could also be structurally altered to represent the control of an outflow from a primary inventory, controlled by a secondary sales or promotion effort. This downstream control of an inventory will have a similar oscillatory response pattern to that of other primary/secondary control structures but with different dynamic characteristics as determined by specific model structures and parameter values. The system could also be in series with other primary/secondary control systems within overall corporate and industry structures, or in parallel with other controlling secondaries such as a capital equipment secondary. While the oscillatory responses of the primary/secondary control structure can be predicted, the total response of the coupled management feedback loops would have to be examined for each specific application.

Another example of this control structure includes its incorporation within an existing environment in order to develop a more desired level of control within existing loop structures. The downstream control of the carrying capacity within a wildlife game preserve is an example of man's use of primary/secondary management within natural systems. In a natural system the carrying capacity of the environment -- food supplies and water -- limit the sizes of animal herds. To avoid the consequences of over populating animal preserves or to avoid the natural responses to certain environmental disturbances, game management systems have been implemented. In addition to the feedback loops related to natural limits and animal and vegetation growth rates, these systems in effect incorporate primary/secondary controls to monitor the food supplies (primary sector) and correct the animal populations (secondary sector) accordingly to avoid over-grazing of the preserve. The exogenous inputs are the delayed effects of environmental disturbances including changes in weather conditions and arable land. The consumption rate would be determined by the controlled herds' consumption rates. The secondary process delays would involve animal gestation periods and relocation delays for secondary inflow changes and the organization and implementation delays of hunting, trapping, and relocating wildlife for secondary outflow changes. While other considerations and existing control loops must be included, this is an example of controlling a primary sector through the incorporation of secondary controls within an existing system.

Because of the wide applicability and its existence within many control environments, the primary/secondary control model should be considered as one of a manager's component control models. The early industrial dynamics studies (1956-66) focused upon negative feedback loop operations as Forrester (5), Fey (7), Roberts (22) and others studied oscillatory behaviors within corporate systems. Before a thorough understanding of negative feedback control system's behavior and its impact upon human attitudes was obtained, the focus of modeling dynamic systems was switched toward the study of positive loop social systems (6,15,20). This thesis re-emphasizes the need for the further understanding of system control by examining this particular negative loop, component control structure and exemplifying an integrated analysis procedure. The control structure under study should be coupled with other well understood control structures for further analysis and understanding of the manager's decisional environment.

The Responses of Primary/Secondary Control

A characteristic of negative feedback control loops is the tendency for the controlled system to oscillate around the desired system state. In a systems analysis of a control model, certain responses are observed that comprise the system dynamic of the simulated model. These responses include the damping ratios, oscillation periods, and excursion magnitudes of a disturbed system's oscillations. The systems analysis of this thesis which integrates the analysis techniques of frequency, time, and statistical analyses, determines the causal influences for these model responses and determines how the responses may be altered by adjusting different parameters or constants representing different management policies or system delays within the control structure. Therefore, the control model may be systematically understood and this understanding can be translated into the different management policies that most effectively control the system with respect to the goals and objectives of an organization.

The management of a system includes the management of resources -- human, material, and monetary -- according to organizational goals and objectives. The systematic approach develops measures of the effectiveness of different control policies in adjusting the system that is disturbed by transient inputs. Therefore, policies are evaluated for their ability to maintain the organizations goals and objectives, and thereby maintain the preparedness of the system to continually face multiple unknown external disturbances. Note that a manager is not implementing a policy to improve the system's damping ratio or decrease the excursions of the oscillations, but instead the manager is utilizing a policy because it has been systematically determined to offer the most satisfactory system control with respect to the organizational goals and objectives. In terms of systems control, the manager of the primary/secondary system is faced with maintaining such things as an acceptable primary inventory, production throughput, secondary labor force, employee training program, employee productivity, monitoring system, cash flow, and profit. For a management environment that experiences multiple disturbances in all these areas, this systems analysis of the primary/secondary control model directs the determination of policies that will give the manager the level of control he or she desires for the particular application of primary/secondary control. These policies make up the managerial dynamic that is imbedded into the structural dynamic of the particular application of primary/secondary control.

The Structural Dynamic

Each application of primary/secondary control will have certain structural differences, but conceptually they still involve the control of a primary flow stream through the adjustment of a secondary accumulation sector. The secondary sector does not act as a simple delay of the manager's attempts to adjust the primary flow stream, as is the case in the direct control of a primary sector. But instead, this secondary sector acts as a momentum term that continuously drives one of the flows in the primary sector. Therefore, the adjustments to the primary flow stream involve adjustments to the momentum of the secondary sector. This momentum adjustment is affected through additional control loops that do not exist in a model of direct control of a primary sector. This inclusion of additional feedback loops within the control structure causes a total system dynamic that is more oscillatory than the system dynamic of a direct primary control model.

The model examined in this thesis is described in the production context; however, because of the wide applicability of this control structure, a more general understanding of the influences of different model parameters or constants is desired. Therefore, different design regions as defined by the various system delays, are investigated for this particular structure. Each primary/secondary control system has a structural arrangement of different system delays. This modeled structure includes a process delay in both the primary and secondary sectors and a delayed information network between the sectors. Different design regions are examined by altering the lengths of these various delays so that the model would represent different production situations. The situations involve longer or shorter production delays, training delays, or information monitoring delays. Certain policy parameters might be consistantly influential throughout all design regions, while other parameters might be more effective in certain design regions. Therefore, the changes in the delay structure of the model will help develop a more general understanding of the influences of different management policies.

It is important to understand that this control structure is being examined in order to understand its dynamic responses before including it within a total management environment. Therefore, if a certain response is desired from this control system, this analysis is able to direct the determination of specific management policies that would provide the desired response. To emphasize the effects of incorporating other control loops within this model, two structural additions were made to the standard control system. While other control loops might be more dominant in their influence upon the primary flow stream, this control structure provides the reference response dynamic for comparison of these other modifications.

Therefore, the system dynamic examined herein is primarily created by 1) the structure of the primary/secondary control system, 2) the magnitudes of the system delays and their arrangement within the control loop structures, and 3) the managerial decisional dynamic. The coupling of a specific managerial dynamic to the implementation delays within a primary/secondary closed loop feedback control structure determines the overall system's response dynamic.

The Managerial Dynamic

A manager's organization is constantly faced with external changes or disturbances that alter the state of his or her system. To counteract the impact of these disturbances upon the desired states of the system, the manager is constantly monitoring the system states and adjusting them to more desirable levels. The responsiveness of a manager to system disturbances is determined by the delay in his or her perception of an error and the time in which he or she desires to see the system adjusted in order to compensate for this error. Therefore, coupled to this decision-maker's organizational goals and means for system adjustment are the time conditions of the delay in error perception and the desired time of system adjustment. This coupling of managerial goals, means of adjustment, perception delays, and adjustment times, forms the managerial dynamic. This managerial dynamic and the implementation delays of a closed loop control system determine the closed loop system dynamic or the total system response to transient inputs.

According to Beer (1), the dynamic response of a disturbed self-corrective system such as this primary/secondary control model, is oscillatory in nature. Rather than be concerned with the overall oscillation of the system, managers are most often concerned with the negative conditions that are the outcome of different phase relationships associated with the system's oscillations -- in the production context inventories may be too large or small as compared to the sales activities, the labor force may be too large or small for the necessary work load, or possibly the cash flow is being too negatively affected by the low level of productivity of the work force. As the manager adjusts the system to correct these possible discrepancies between the system states and the goals of the organization, the manager sets in motion the dynamics that will govern whether the system will be corrective toward a state of relative equilibrium or whether the system will continue long term patterns of sustained oscillations.

The manager is usually aware of the goals of the organization -- in the production context they might include desired inventory levels for different sales levels, cash flows, profitabilities, and productivity levels. And the manager usually has methods for altering most discrepancies, such as increasing or decreasing productivities and increasing or decreasing work force levels. However, a manager is less aware of the time relatedness of his actions that might be the cause for a sustained oscillation around a desired state of relative equilibrium. The time related management policies regarding time horizons for system monitoring and adjustment times for the correction of system's errors coupled to the organizational goals and the means for system adjustment determine the overall dynamic system response. Adjustments in these time related management policies will alter the oscillatory response of this self-corrective system, as will be demonstrated in the simmulation tests of the primary/secondary control model.

Many theories focusing upon decision-making strategies ignore the time relatedness of managers' actions. To economists and maximizers decision-making begins with a problem, explicit goals, and all possible courses of action and their consequences laid out before the manager. A mere evaluation of consequences with respect to a ranking of alternatives in terms of goal achievement, expected benefits, and expected costs, allows the decision-maker to apply a simple optimization strategy to the problem.

However, in systems' operations the manager is seldom faced with a single problem or disturbance. He is usually experiencing multiple disturbances in such areas as sales and inventory levels, cash flows, and employment levels. System goals may be established by some optimized strategy, but system adjustments toward these goals are carried on throughout operation with continuous system disturbances. The responsiveness of the managerial dynamic and the responsiveness of the total system will determine if the system will experience a strong amplification of exogenous disturbances or whether the system will maintain a strong controlled stability throughout the operation of maintaining system goals. The responsiveness of the control structure, as determined by the time relatedness of a manager's actions, is of continuing importance long after the determination of any optimum goal levels.

Other objections have been raised against the assumption that the optimizing strategy even provides an accurate descriptive model of how people actually do make decisions. Simon (24) refers to the manager as a "satisficer" rather than a maximizer; as such he looks for an alternative that is "good enough" to meet a minimal set of requirements. Cyert and March (4) suggest that with more uncertainty about a long-term outcome, there is a greater tendency to make a policy decision on the basis of its short-term acceptability within the organization. Johnson (11) adds that often executives have to forego the optimal decision in favor of a more conventional "second best" choice because it will cause little immediate disturbance or disapproval and will be more easily implemented.

Janis and Mann (10) add that the decisional stresses upon a manager greatly affect his information processing and decisional capabilities. These stresses might drive a manager to overreact under extreme system conditions and underreact during periods of relatively stable system conditions. Decisional stresses may alter the manager's time horizon relative to system monitoring such that during extreme system conditions the manager may look at only the most recent system measures rather than weigh them against long term system trends. Policy changes made because of high stress situations will be shown to change the dynamic responses of the system.

Simon (3) argues that the satisficing strategy fits the limited information processing capabilities of human beings. He says the world is inhabited by people of "bounded or limited rationality" who constantly resort to gross simplifications when dealing with complex decision problems. As a satisficer the decision-maker has to only consider alternative courses of action sequentially until one that "will do" is found to implement.

Implementation becomes the focus of the "incrementalist" and "muddler". Miller and Starr (16) assert,"that over time both individuals and groups may be better off to move in incremental steps of reasonable size toward the perceived and bounded optimum rather than take giant strides based on long-range perceptions of where the ultimate optimum exists" (p. 51). Lindblom (2,12,13) refers to this as "the art of muddling through" as the incrementalist sticks close to his familiar path of policy making showing his preference for the sin of "omission" over the sin of "confusion".

In maintaining system operations, adjustments to the system appear to be of an incremental nature. Again, the question of the label of the type of decisional strategy is not sufficient to describe the system operation. While the manager may make incremental system adjustments toward optimal system levels, two questions must be answered to understand the dynamics of the system. When does the manager perceive an adjustment to the system must be made, and how large an adjustment does he make? The answers to these questions determine much of the responsiveness of the system to perceived disturbances.

Rather than seek optimum solutions of system operation, this thesis focuses upon a methodology to determine preferred means of control of system states around given desired levels. This thesis examines the influences of the managerial and structural dynamics upon the total system's response in the context of a particular, well defined, goal oriented control structure. A digital computer and the DYNAMO compiler are utilized to handle discretized solutions to differential equations. A system analysis including the tools of frequency, time, and statistical analyses is used to demonstate an integrated feedback dynamics methodology and examine particular managerial and system dynamics through the operating characteristics of the model simulations. The significance of different managerial dynamics is demonstrated with respect to the responsiveness of this primary/secondary control system and its ability to maintain organizational goals and objectives.

General Problem Statement

This thesis examines the dynamic characteristics of a structured primary/secondary control model relative to parameter adjustments and relates the model to real managerial environments. It exemplifies the integration of frequency, time, and statistical analyses as tools of a feedback dynamics methodology, utilized here for the analysis of a linear feedback control system. The concept of control of a primary flowstream by a secondary sector recognizes the inability to directly change the inflow to a primary sector without first changing the level of the secondary sector. The results of the analysis of the primary/secondary control model direct the redesign of the system for specific control situations. Each procedure of the analysis methodology adds further clarification to the causal relationships within a particular system dynamic. The dynamic characteristics observed and measured from the DYNAMO simulations (time analysis) of the model include for a systems perspective, the model's approximate natural frequency, damping ratios of key variables, and magnitudes of first excursions from desired system goals after a step function input. From a management perspective the DYNAMO simulations provide economic measures of different systems' operations. The statistical analysis focuses upon the dominance of certain model parameters or constants with respect to their ability to alter the model's response to transient inputs. The frequency analysis of a system parameter set determines the natural frequency and bandwidth of the system, the system gain, the high frequency cut off point, and the tendency for the system to continually oscillate, attenuate, or become unstable. The primary/secondary control model is a managerial component control model to be coupled with other decision models to better understand the managerial environment. The purpose of the system's analysis and design recomendations is to assist the manager in the redesign and restructuring of his primary/secondary control situation and exemplify the integrated feedback dynamics methodology for the analysis of a decision maker's environment.

CHAPTER III
METHODOLOGIES AND APPROACH

Feedback dynamics is the study of the information-feedback characteristics of socioeconomic systems to show how organizational structure, amplifications in policies, and time delays of decision-making and implementation interact to influence the operation of the system. Feedback dynamics as a philosophy is a way of looking at how the world is structured around continually operating information-feedback loops. A feedback dynamics analysis of a complex nonlinear system includes an approach that integrates time, frequency, and statistical analyses of a modeled system to more thoroughly understand the existing structure of information-feedback loops and determine the dominant causal relationships within a system.

Recognition of the existence of closed feedback loops in any socioeconomic system is one of the corner-stones of the feedback dynamics approach. Forrester (5) wrote, "An information-feedback system exists whenever the environment leads to a decision that results in action which affects the environment and thereby influences future decisions" (p.14). The study of feedback systems deals with the way information is used for the purpose of control. An understanding is developed as to the amount of corrective action taken and the time delays between the implementation of interconnected decisional components can lead to undesirable or unstable system operations.

Information-feedback loops are composed of physical and information accumulations, physical flow rates, and information networks. Accumulations are variables that measure quantities which would be countable if the system were brought to rest. Inventories, employment levels, and units in production are common examples of physical accumulations, while the averages of sales, inventories, and employment levels are compiled in information accumulations. Flow rates in and out of physical accumulations cause them to vary with time.

Accumulation levels, in turn, affect the observations within the information network entering into the decision processes which control the system flow rates. Finally, changes in the values of system flow rates produce new levels within the accumulations. This sequence closes the system loops. The above changes in flow rates and accumulations are not produced instantaneously. Inherent delays exist between the time the action is taken and the time the response is observed. These delays appear at all decision points, within information networks, and within unit flow streams.

Information networks coupling system accumulation measurements to decision points at system flow rates are often segmented in the modeling process to distinguish the various functions within the information and decisional networks. Functions might include the averaging of information, the comparison of system states to desired goals (error calculations), adjustments in system pressures for desired system states, or actual adjustments in system flow rates. While it is not always necessary to segment these individual calculations to determine system flow rates, the system is more clearly described and understood if the auxiliary functions are broken out into either auxiliary equations or information accumulation equations. Therefore, the feedback control loops examined include system flow rates into and out of physical accumulations and the information networks including functions of system state measurements, goal comparisons and calculated alterations of the system flow rates. A simple primary negative feedback control system exemplifying these component parts is shown in Figure 1.

Information-feedback loops can be of two types, positive or negative. When an increasing (decreasing) accumulation leads to a varying flow rate which makes the accumulation increase (decrease) even more, the feedback loop is positive. On the other hand, if an increasing (decreasing) accumulation leads to a varying flow rate which makes the accumulation decrease (increase), the feedback loop is negative. The positive feedback loop is related to a growth process, while the negative feedback loop is related to a goal-seeking or control

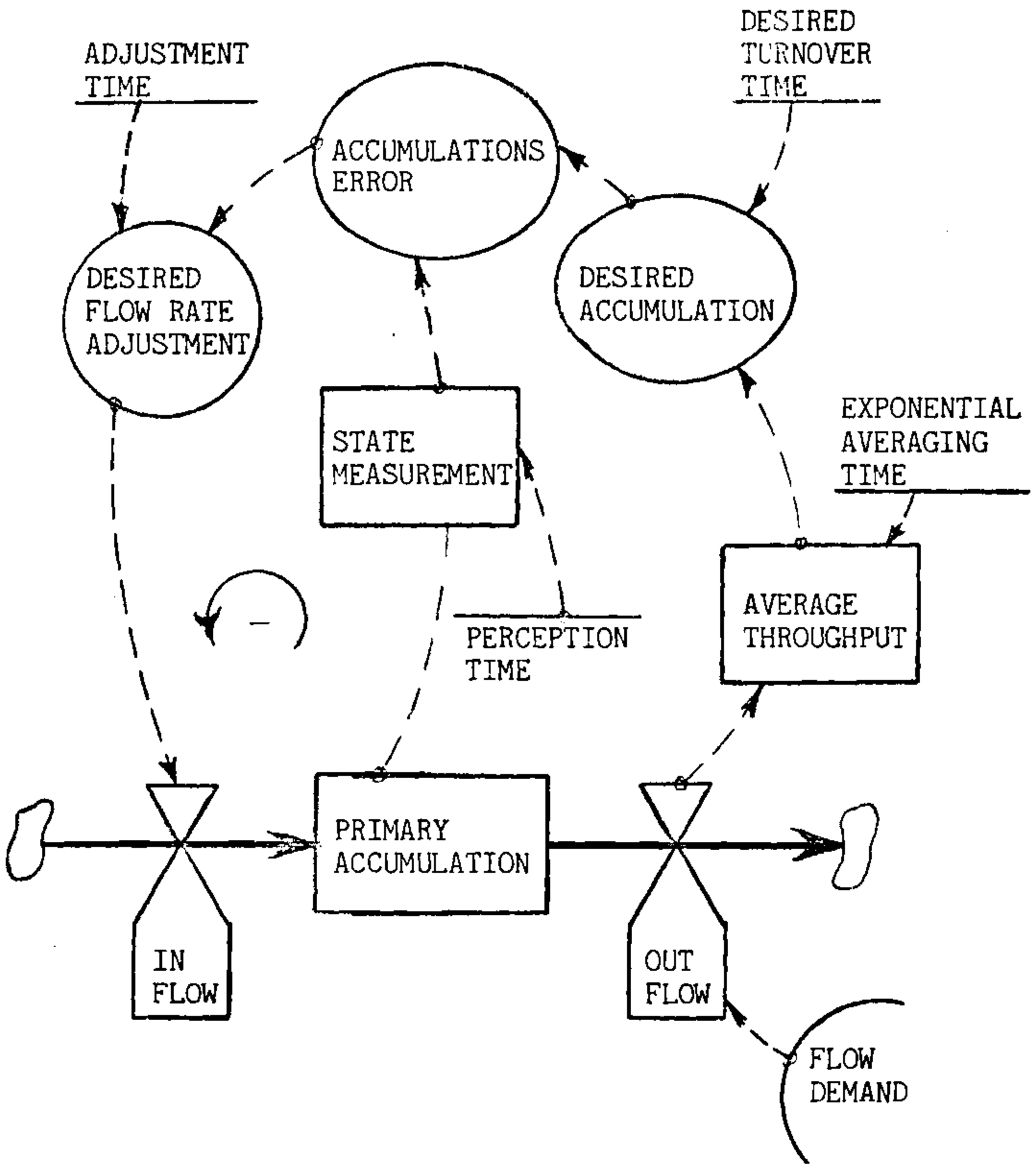

Figure 1. Primary Negative Feedback Control System

process. As previously stated this thesis will be analyzing a particular structure of negative feedback loops.

Analysis Procedure

A feedback dynamics model is comprised of a large set of linear and nonlinear differential equations for which there are no closed form solutions. There are two ways to analyze such a system. The first is to approximate the differential equations representing the feedback system with difference equations and simulate the equations' response on a digital computer. In this way the nonlinearities can be preserved and the accuracy of the approximation can be made as high as necessary by shortening the solution interval. The model can then be the subject of experiments to deduce the system's behavior, but no analytical methods or solutions are possible.

The second procedure involves a formal control theory analysis, frequency analysis, of the linear incremental counterparts of the original linear and nonlinear differential equations. Because of the complexity of this linearly approximated system, analytical methods do not determine system measures as literal functions of system parameters. However, utilization of numerical solution techniques greatly assist in the further understanding of the responses of a control system.

System Analysis of Model Simulations

The simulation studies described in this thesis involve 1) the examination of systems' responses to transient inputs, 2) the study of parameters' dominance of system control, and 3) the study of the influence of parameter design regions upon the response of the system. The transient responses of the examined system point out the approximate natural frequency of the system's oscillations, the system's damping characteristics, the phase relationships between variables, and the percentage variations of important variables. An orthogonally designed experiment of system parameters specifically altered for model simulations, enables the statistical determination of the dominance of certain parameters in altering the dynamic responses of the system. Further examination of parameter design regions completes a more general development of conclusions regarding many applications of primary/secondary control.

The use of orthogonally designed experiments of changes in model parameters allows the analysis of more than one parameter at a time while determining relative parameter dominance. The experiments involve a fixed percentage ($\pm 25\%$) alteration of specific model parameters arranged orthogonally for simulation reruns. Stepwise linear regressions upon the output data of the model simulations of certain variables' damping characteristics, magnitudes of peak excursions, and periods of oscillations demonstrate the dominance of certain parameters in controlling these specific independent system measures.

The output of the statistical regressions includes the parameters' coefficients for the linear regression equation and the t and F statistics regarding the significance of the coefficients of the regression equation (all parameters had to be significant to .05 or less). More importantly, the regression analysis determines the explained variation of the dependent variable attributed to each parameter in the regression equation. Since each parameter tested experienced the same twenty-five per cent alteration, the percentage of explained variation of a dependent variable attributed to a parameter is then a measure of the percentage dominance of that parameter with respect to controlling that particular system measure in relation to the other altered parameters in that experiment.

In addition to testing the effects of small alterations to parameter values, parameter design regions were also examined to determine what would be the effects upon the primary/secondary system's response and specific parameters' dominance if certain parameter values were altered drastically. This would occur in the case of different applications of primary/secondary control. The alterations made to determine statistical dominance of certain parameters were relatively small in order to stay within approximately linear regions of the system measures -- damping ratios, excursion magnitudes, and periods of oscillation. However, severe alterations of the delays within the control loops (changing delay time parameters) set the system within a different design region. Changing regions would be like describing a different control system application with different unit processing delays, different employee training delays, and different monitoring or error perception delays. From comparing parameter dominance tests of different regions, regional influences can be observed with regard to the general conclusions of a primary/secondary control structure.

Added to the equations for the simmulation of the primary/secondary control model are equations that provide certain simple financial measurements of each system's operation. Because of the general scope of the model, only relative measures were designed, including the cummulative payroll expenses, the cummulative processing expenses, and their summation in the cummulative labor costs. These measures were used in order to better relate the economic significance of the design changes recommended as a result of the system's analysis. They emphasize the effects of different prescribed management policies. Further development of these measurements would be necessary to evaluate the analysis of a specific application of primary/secondary control.

Therefore, this system's analysis helps develop general and specific conclusions regarding parameter influences within primary/secondary control systems. The simulations of the primary/secondary model offer state and performance measurements of the system. The orthogonally designed experiments of parameter changes demonstrate the dominance of parameter influences for specific design regions. Comparisons of the dominance of parameter influences between design regions show the influences that are only regionally observed rather than generally experienced by all primary/secondary control systems. Financial measurements of the system's operations emphasize the economic significance of recommended design changes.

System Frequency Analysis

The frequency analysis of the system determines the natural frequency and bandwidth of the system, the system gain, the high frequency cut-off point, and the tendency for the system to continually oscillate, damp out, or become unstable. The frequency analysis is performed mathematically by forming the system transfer function from the Laplace transforms of the linearized incremental equations which approximate the original nonlinear set of difference equations. Such a function relates the behavior of one variable to the behavior of any other. Usually the transfer relation between the input and the principal variable of interest is determined.

The mathematical expression of the transfer function will include only system parameters and the Laplace frequency variable, s, in the form of a polynomial in s divided by a different polynomial in s.

$$\text{TRANSFER FUNCTION} = \frac{E(s)}{I(s)} = \frac{s^n + a_{n-1} s^{n-1} + \ldots + a_1 s + a_0}{s^m + b_{m-1} s^{m-1} + \ldots + b_1 s + b_0}$$

$E(s)$ -- Laplace transform of the important variable
$I(s)$ -- Laplace transform of the input time function
a_i -- Real constants related to the system's parameters
b_j -- Real constants related to the system's parameters
m -- Integer greater than n for realizable systems
n -- Integer
s -- Laplace frequency variable

An alternative form of the transfer function is:

$$\text{TRANSFER FUNCTION} = \frac{(s+z_1)(s+z_2) \ldots (s+z_n)}{(s+p_1)(s+p_2) \ldots (s+p_m)}$$

s -- Laplace frequency variable
z_i -- constants (real or complex) related to the system's parameters
p_j -- constants (real or complex) related to the system's parameters

The p's are called the poles of the system, the z's are the zeros.

Three important results are desired from a frequency analysis -- 1) the value of the poles as literal functions of the system parameters, 2) the magnitude of the transfer function as a function of "w", the radian frequency, and 3) the ultimate state responses to the step and sine inputs as literal functions of the system parameters. But, because the order of the polynomials of the transfer function in most feedback dynamics models is greater than four, there are no analytical solution methods to determine these values as literal functions of system parameters. However, the use of numerical solution techniques to solve for the poles and zeros of the transfer function and the transfer function as a function of w still yield valuable information.

Numerical solution techniques for solving higher order polynomials, are able to determine the poles and zeros of the transfer function. The poles of the transfer function are those values of "s" which make the denominator equal to zero. The forms of these poles determine the overall type of system response. Negative real poles correspond to declining exponential responses to transient inputs. Positive real poles imply rising exponential behavior. Complex conjugate pole pairs designate oscillatory behavior with a declining amplitude when the real part is negative and an expanding unstable amplitude when the real part is positive.

Changes in the positions of poles on an s-plane pole diagram caused by parameter manipulations further demonstrate certain system response tendencies. Plotting the poles of a system transfer function of one system parameter set on an s-plane diagram and then changing a single parameter value demonstrates the effect of that one parameter upon the poles of the system. These changes might be in the form of changing the frequency response attributed to a complex conjugate pole pair or possibly changing two negative real poles representing declining exponential responses into a complex conjugate pole pair depicting a more oscillatory tendency within the system. Changes might also include moving a complex conjugate pole pair through the positive and negative regions of the real axis depicting the changing damping characteristics of the system including less stability as the pole pair moves toward more positive values. If the higher order polynomial of the denominator of the transfer function could be factored, then the system control loops' damping constants and natural frequencies could be expressed as literal functions of the system parameters.

Additionally, the use of the system transfer function is found to be very important in determining the range of frequencies to which the system is particularly sensitive (bandwidth), the ability of the system to reject high frequency disturbances (high frequency cut-off point), and the system's steady state response amplification of specific frequencies of sine wave inputs. Parameter experiments within this frequency analysis help determine parameter adjustments to improve the system's response to high frequencies, the bandwidth of frequencies for which the system is particularly sensitive, and the amount of amplification of system inputs that the system experiences.

The information about the system derived from the frequency analysis cannot be obtained or is not easily obtained from the time analysis of the model simulations. However, the results for system frequency response, damping characteristics, high frequency cut-off point, frequency bandwidth, and input amplification are extremely helpful during a system redesign phase. Therefore, the utilization of information from a frequency analysis integrated with the results of model simulations and parameter dominance analyses, provides a clearer picture of the system's total response nature and the causal relationships of most importance in altering the total system's response.

CHAPTER IV

A MATHEMATICAL MODEL OF PRIMARY/SECONDARY CONTROL

A mathematical representation of the relationships within a primary/secondary control model is described here. This is a study of a structural model and therefore only the factors which enhance a clear understanding of the structural relationships are included. Therefore, the relationships which were selected and the reasons behind their selection are taken up first. A brief discussion of the mathematical form precedes the derivation of the complex equation set.

Extent of the Model

In a model it is necessary to include a minimum amount of structural detail in order to represent the major causal forces and not obscure the important relationships with detail not relevant to the dynamics of the examined feedback structure. The system parts used within this primary/secondary control model designed in the context of a production system simply represent the flows of produced units, production employees, and information. A diagram of these flows is shown in Figure 2. An additional diagram showing the direction and the sign of the influence of the various model components upon other components is shown in the influence diagram of Figure 3.

The influence diagram of Figure 3 depicts more clearly the presence of the feedback control loops. A positive influence between variables means the influenced variable changes in the same direction as the influencing variable. Likewise, a negative influence means the influenced variable changes in the opposite direction as the influencing variable. The sign of the feedback loops as previously described and as depicted in Figure 3 can be easily determined by counting the presence of negative influences in the loop. The presence of an even number of negative influences within a loop signifies a positive net influence within the loop. An odd number of negative influences signifies a negative net influence within the loop.

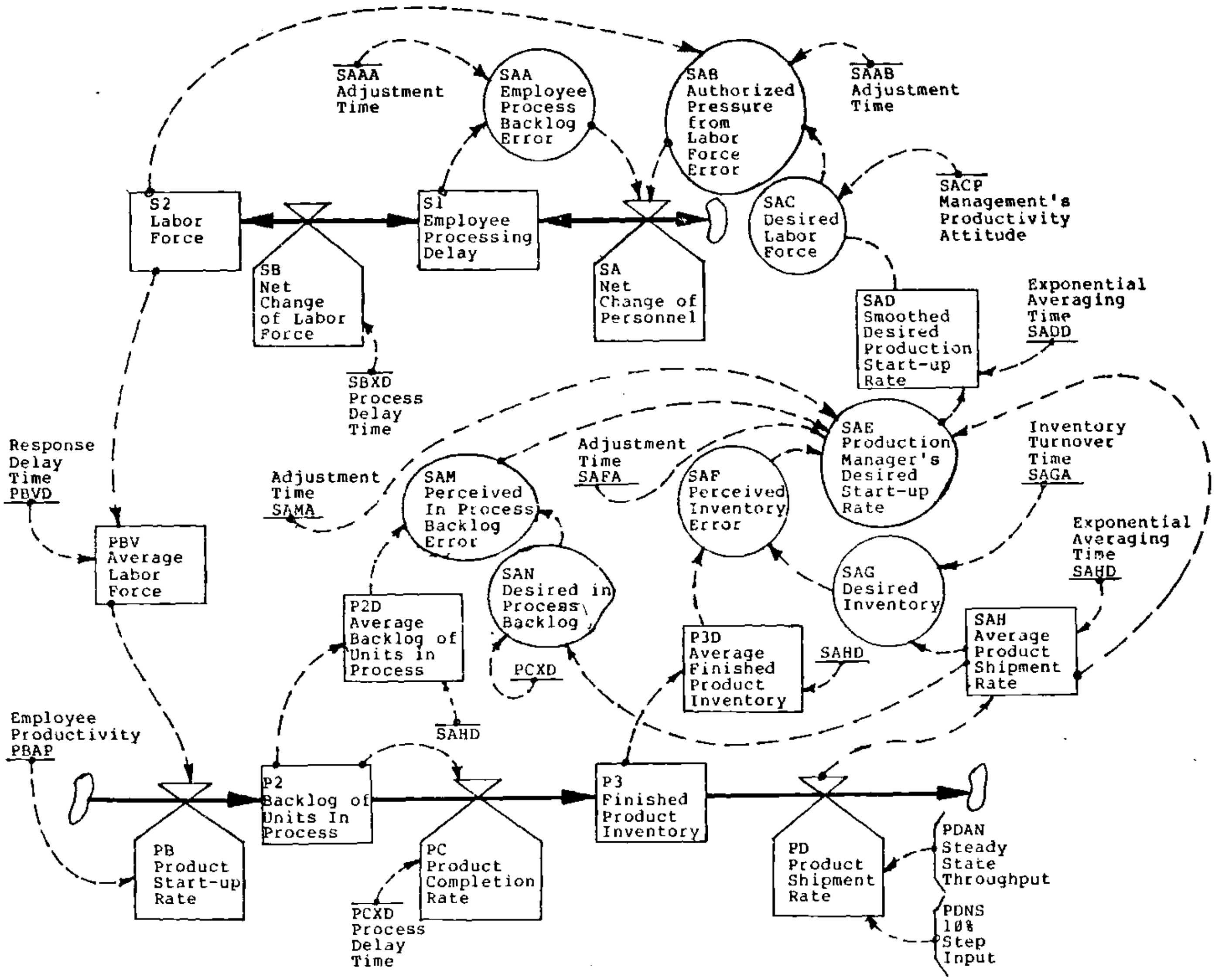

Figure 2. Flow Diagram for Primary/Secondary Control Model

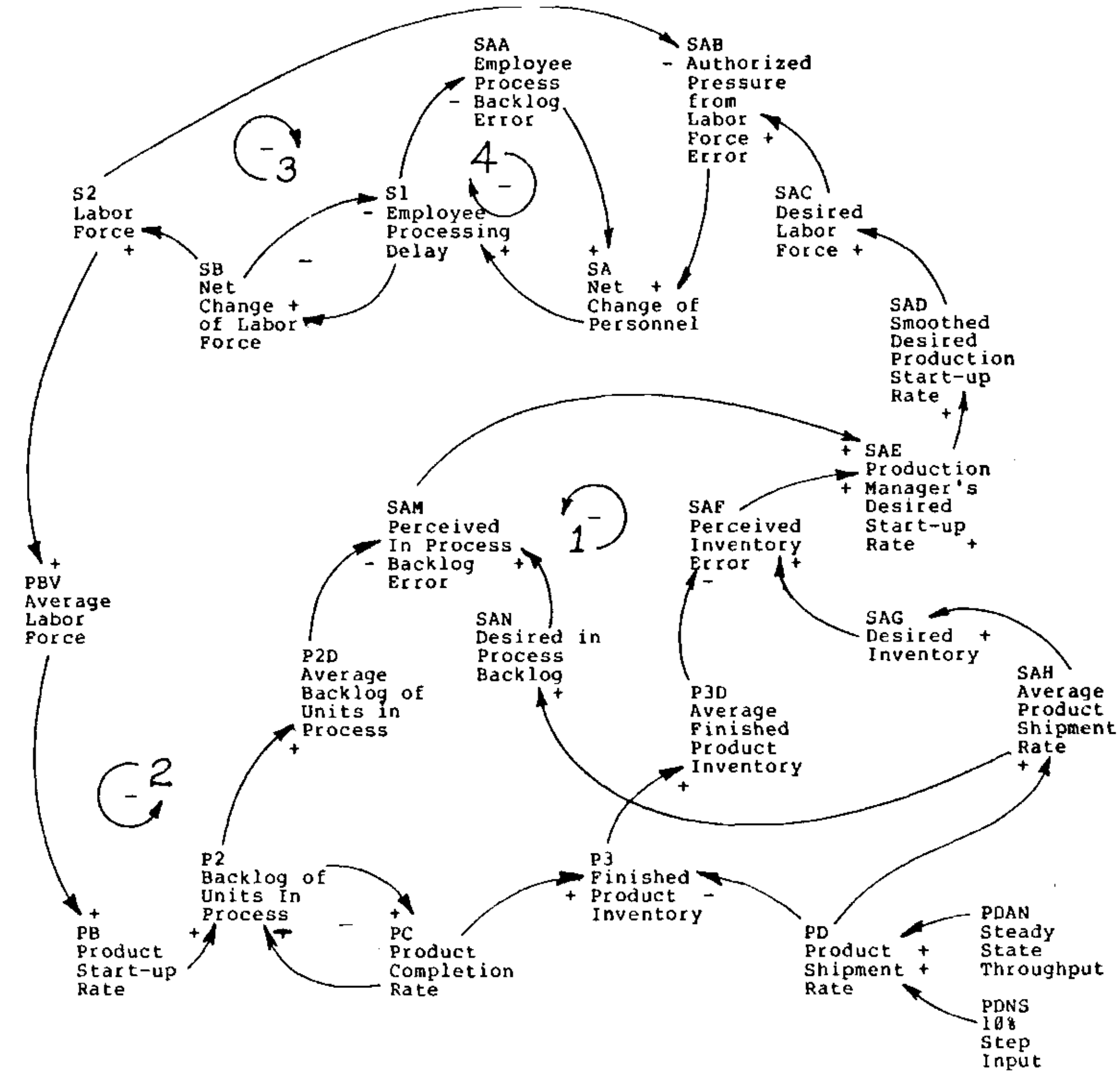

Figure 3. Influence Diagram for Primary/Secondary Control Model

The traced paths of influence, not material flows, determine the feedback loops of a system. A variable's influence is not always in the same direction as the material flow within the system. This can be seen by the direction of the influence an outflow of an accumulation has upon that accumulation.

The primary/secondary control model includes four control loops (negative) and two first order delay loops (negative). The control loops are refered to by their functions -- 1) the primary inventory control loop, 2) the primary process control loop 3) the secondary work force control loop, and 4) the secondary process control loop. The first order delay loops coincide with the functional process delays in the model. The characteristics of each loop help determine the overall dynamic response of the model.

The primary or production sector as shown in Figure 2 signifies the delay of processing raw materials into completed units and the inventory of these finished units. This sector does not include the control of the preceeding raw material inventory because this consideration would not add to or subtract from the question of secondary control of production when there is a sufficient inventory of raw materials. This sector also does not include marketing considerations that would alter the outflow from this sector because this is comparable to adding a downstream secondary representing the sales force for adjusting sales levels. The components included in this sector were chosen and designed to enhance an understanding of the general structure of interest -- secondary control of a primary flow stream. Therefore, only the components included in the flow stream contol by the upstream secondary are included in order to simplify the focus of the model.

The secondary sector includes the production workforce on the job or in training and the information and decisional networks determining desired and actual changes in the workforce. The model decisions do not include financial considerations or pressures but instead focus upon getting the necessary work done. However, to better understand the financial implications of different management policies, certain operating costs as previously described were accumulated in order to offer economic system comparisons. The labor force is also not divided into skilled or unskilled laborers or grouped in any way by task. Instead the overall assumption that each employee contributes an equal portion to the production capacity of the operation is made in order to simplify this early examination of the dynamics of a primary/secondary control system. In effect this sector simply includes the decisions for determining the desired secondary levels, the means for altering the secondary level, and the controlled secondary accumulation.

The study is thus focused on the primary or production flow stream as controlled by the level of the capacity of production within the secondary sector or labor force. The model has been designed for analysis of the operating feedback loops upon the basis of two principles:

1. Omit all detail not necessary for the analysis of the operating characteristics of this particular control structure.
2. Include those functions that operate within the influence of the important information feedback loops of the general primary/secondary structure.

Equation Characteristics

The equations of the primary/secondary control model quantitatively represent the significant relationships of the system. Difference equations are utilized for the model simulations while equivalent incremental differential equations are necessary for the frequency analysis. The equations represent the aggregate flows of orders, materials, men, and information. The equations representing the management decisions, mathematically represent the intent of the management process but not necessarily the specific quantifications, if any, of the manager.

The difference equations used in the model simulations are no higher than first-order and must be solved sequentially (not simultaneously in matrix form). Each variable is represented by an equation and a value for each variable is found at each solution time. These solution times are seperated by the computational time interval, DT (Delta Time). The simulation solution is calculated by the DYNAMO (4.11) compiler program for the CYBER 70 Digital Computer. The equations may be nonlinear when necessary to represent actual operation.

Three equation types represent the component variables in the simulated system -- accumulations, rates, and auxiliaries. Accumulation equations have a single time subscript indicating the variable takes on its value at a specific instant of time (K is taken as the present instant, J is the instant preceding K, and L is the instant succeeding K with a time interval, DT, separating J from K and K from L). Rates representing flows of orders, materials, or men (units/week, men/week, etc.) are subscripted by double letters to indicate that the variable takes on and holds its value during the computational time interval specified (J to K or K to L). Auxiliary equations segment according to physical significance the consolidation of combinations of variables influencing rates. Auxiliaries have a single time subscript signifying their values apply only at the calculation instant. Note that if the system were frozen at the computational instant accumulations and auxiliaries would be given values while all flow rates would be zero. It is important to re-emphasize that even though the standard time units are in weeks throughout this discusion, the units of time are significant only to the determination of the magnitudes of the parameters used. The magnitude relationships between the parameter adjustment times and the model delay times are the relationships that must be maintained if time units are switched for different control applications. Therefore, depending upon the application, process and delay times could be in days or months while unit flow rates could be in units/day or units/month. Accumulation levels, flow rates, and conversion parameters would also have to be at their appropriate magnitudes. The particular time units used would be dependent upon the specific application within a design region.

These difference equations are simulating an hypothetical but realistic control system, and therefore, initial values must be provided as starting points for the variables represented by first-order accumulation equations and certain rate equations. These values are determined from calculations extending from the assumption that the system is initially in a steady undisturbed state while maintaining a constant throughput for the system. In this way all of the variation during the simulation can be attributed to changes in the input function.

Part of the integrated analysis methodology employed is based on linear control theory. Therefore, each difference equation must be represented in linear continuous form. The Laplace transform of the linear, continuous counterpart of each difference equation is given in the equation derivation. This is called the transformed linear equation.

The most important property of linear equations or systems is that of superposition. This characteristic makes it possible to analyze the system behavior for any one input independently of all other inputs and for any scale range. An extension of this principle implies that the output of a linear system cannot include frequency components which were not present in the input signal. This principle and others have led to the development of many formal analysis and synthesis procedures which make it possible to learn quickly a great deal about the behavior and potential improvements of linear systems.

Nonlinear system analysis has produced few general analysis procedures or solution techniques. This, according to Fey (7), is because of the great difficulty in dealing with systems in which 1) changes in the scale of the input can cause major changes in system behavior, 2) frequency components which are not present in the input can be generated in the system, and 3) the response to one input component may be directly related to the response to all other parts of the input.

The present structure of the primary/secondary control model only includes linear equations and the analysis centers on the understanding of the linear responses to transient inputs. However, further analysis of this structure should include the nonlinear relationships that alter management's policies and change employee productivities under stress conditions. To further the understanding of primary/secondary control, the frequency analysis applied on this linear system of equations should be utilized to examine those nonlinear systems of equations that are able to be expanded using Taylor methods. The two approaches to systems analysis that are applied here on this linear system of equations, should be employed where possible to analize nonlinear systems.

The first analysis approach includes the formulation of difference equations which allow for the preservation of all system nonlinearities. Simulation of the system behavior under different input conditions is an attempt to gain an understanding of how the system operates. Utilizing orthogonally designed experiments of parameter changes, allows further statistical determination of parameters' influences and their dominance with respect to the control of the system along with demonstrating overall system performance. Based on the understanding gained, changes can be made in the system so that the improved system's simulation results can be compared to previous standard results. This experimental method of analysis can always be used on any feedback system's set of nonlinear equations.

The second method of analysis is to linearize the nonlinear system or the control loops of interest and proceed with a classical linear analysis of a feedback system. The equation linearization is done by taking a Taylor series expansion of the equations about the operating values of the variables while neglecting the higher than first-order powers of the variables. When this is done, the variables used are "incremental" variables rather than total variables. Thus the variable represents the deviation from the average (or steady state) value rather than the total absolute value which also includes the average value. This linear, continuous form of the differential equation is then used for the development of the transformed equations.

This method of linearizing the system of equations is satisfactory provided the excursions of the variables remain in the relatively linear region near the variables' average values. As the deviations become greater, the assumptions of linearity are less accurate and the modes of behavior caused by the nonlinear relations are not represented in the system's expanded linear counterpart. In the equation derivation that follows, both the total difference equations and the transformed, incremental, linear differential equations are presented. Because the primary/secondary control system studied is presently in a linear form, there is no need to include a separate linearized version of the difference equations.

Assumptions and Limitations of the Model Analysis

This general control structure exists in many areas and is of interest because of the possible dynamics related to its operation. While overly damped primary/secondary control systems are extremely sluggish and have little dynamic importance, responsive primary/secondary systems are typically oscillatory in behavior and easily influenced by changes in management policies. Many internally varied policies might also alter the system's responses; however, this analysis will not thoroughly examine the existence of such pressures to change policies. Here the general structure of primary secondary control will be examined along with the influences of different management policies including information time horizons (information delay times) and error adjustment times.

While this model analysis is completed in the production context of primary/secondary control, it is not a complete representation of the production control process. A more complete production model would include the internal control loops regarding the pressures altering productivity, variable employee processing times, employee attrition rates, and variable time horizons and adjustment times. The secondary would be structured to include different flows for hiring, firing and attrition rates and different levels of skilled and unskilled labor. Other controlling secondaries such as capital equipment might also be included in parallel with the work force secondary. The primary sector could include an order backlog accumulation and the capability of shipping directly from finished process as compared to shipping from inventory. Therefore, specific applications of primary/secondary control would have certain individual design considerations in addition to this general control structure described here.

The secondary sector was designed to directly alter the production start-up rate. Therefore, it indirectly altered the production completion rate through the in process delay. This assumption is related to the inability of a system to produce more units than have already begun the earlier stages of process. This process delay may be increased in its order of delay to represent the specific type of delayed response to the change in production start-up rate.

Forecasting techniques for establishing desired system state levels were restricted to evaluating past shipping rates. Expanded forecasting methods might include trend extrapolation, estimates of minimum and maximum demands, and the use of geometric relationships between desired inventories and increased sales levels. However, the forecasting technique used here is satisfactory as a driving mechanism because this system analysis primarily focused on relatively small disturbances for an approximately linear range of system operations.

Therefore, once the influences of the structural and managerial dynamics upon the responses of this basic primary/secondary control structure are understood, the analysis of an expanded model to include these additional considerations is more easily completed and understood.

Model Equations

The equations of the primary/secondary control model are derived in this section. Each equation has three different forms and they are presented together in this order.

1. the total difference equation
2. the Laplace transform of the linear, incremental difference equation
3. the value of the variable in its initial steady state condition

Simulations of the model are run using the first and third equation forms. The transfer function for the frequency analysis utilizes the second equation form.

Each equation will be sequentially numbered for further identification. The type one equations will be labeled "L" for level or accumulation equations, "R" for rate equations, or "A" for auxiliary equations. The transformed equations of type two will be labeled by a "T". Only those variables -- accumulations and some rates -- requiring an initial value for simulation will have a type three equation labeled by an "N". Additionally the initial values of the other equations will be listed for reference only, as calculated by the DYNAMO compiler and designated here by an "I".

The variables have been grouped into either the primary or secondary sectors and labeled accordingly. The variable labels are loosely derived from an alphanumeric coding style that distinguishes the influence of variables and the system information and physical flows, rather than mneumonically approximating a variable name. This coding system simplifies the model explanation and the early phases of model development and trouble shooting.

Briefly the alphanumeric coding adds to the distinction of model sectors and the types of variables -- levels, rates, auxiliaries, and parameters. The first letter of the label signifies the specific sector (here "P" for primary and "S" for secondary sector variables). The second and last figure of a physical accumulation or level is a number designating position within the flow stream. The second and last figure of a rate variable is a letter alphabetically designating position within the flow network beginning with the origin of the flow stream. All auxiliary and information accumulations have specific significance to one or more rate variables. Therefore, the auxiliaries' third and last letter is added to the label of one of the influenced rate variable's labels in an alphabetical sequence designating influence to the rate. (auxiliary SAA.K and SAB.K are included in the rate equation of SA.KL while SAC.K is included in the equation of SAB.K). Model parameter or constant labels are four figures long including a designation of the rate or auxiliary they are used with in the first three figures. Any letter in the fourth position is used to distinguish the parameter from any other parameter for that influenced auxiliary or rate (here "D" for delay times, "P" for productivities, "S" for input steps, and "A" and "B" for adjustment times and other necessary constants).

The derivation of model equations follows and a complete list of model equations is in Appendix A and B demonstrating the alphanumeric coding style of distinguishing model sectors, variable types, and influence sequences.

Primary Sector

The primary sector represents the unit flow stream in a production environment. Six variables are included in this sector including the product shipment rate, finished product inventory, unit completion rate, in process backlog, unit start-up rate, and the averaged or smoothed labor force. The product start-up rate is one point at which the sectors are coupled. A constant productivity is applied to an average labor force to approximate the inflow to the production flow stream.

```
PB.KL=PBV.K*PBAP                        (1R)
PB   =PBV*PBAP                          (2T)
PB   =1000  (units/week)                (I)
```

PB -- product start-up rate (units/week)
PBV -- average or smoothed labor force (men)
PBAP-- employee productivity (5 units/man-week)

A variable for the average or smoothed labor force was used to represent the full productive strength of the work force. This was based upon the assumption that changes within the level of the work force caused short term organizational disturbances that would affect the productivity of the workforce. While avoiding at this time the inclusion of a variable productivity, this delay equation compensates for the disturbances to productivity caused by additions or subtractions to the work force. The smoothed labor force was calculated by taking an exponentially weighted average of past work force levels.

```
PBV.K=PBV.J+(DT/PBVD)*(S2.J-PBV.J)      (3L)
PBV  =S2/(1+PBVD*s)                     (4T)
PBV  =S2      (200 men)                 (5N)
```

PBV -- average or smoothed labor force (men)

PBVD-- response delay time (4 weeks)
S2 -- labor force (men)
DT -- Delta Time (0.5 weeks)
s -- Laplace frequency variable (radians/week)

The in process backlog represents the accumulation of all unfinished units within the production process. The delay time of this accumulation emphasizes the time a unit would spend in process considering units held in queues before further processing. The value of this accumulation is determined by taking the algebraic sum of its value at the previous computation instant, plus all units started into production, minus those units completed and placed into inventory during the previous computation interval.

P2.K=P2.J+(DT)*(PB.JK-PC.JK) (6L)

P2 =(PB-PD)/s (7T)

P2 =PDAN*PCXD (8N)

P2 -- backlog of units in process (units)
PB -- product start-up rate (units/week)
PC -- product completion rate (units/week)
PCXD-- process delay time (2 and 12 weeks)
PDAN-- steady state throughput (1000 units/week)
DT -- Delta Time (0.5 weeks)
s -- Laplace frequency variable (radians/week)

The combination of the backlog accumulation and the product completion rate make up a first-order exponential physical delay. Units held in the backlog accumulation are processed at a rate equivalent to the value of the accumulation divided by the time they are delayed in process. Changes in the level of the backlog accumulation are therefore reflected in changes of the completion rate.

PC.KL=P2.K/PCXD (9R)

PC =PB/(1+PCXD*s) (10T)

PC =1000 (units/week) (I)

P2 -- backlog of units in process (units)
PB -- product start-up rate (units/week)
PC -- product completion rate (units/week)
PCXD-- process delay time (2 and 12 weeks)
s -- Laplace frequency variable (radians/week)

In the actual simulation of this model this set of equations representing a first order delay accumulation was expanded to a third order delay accumulation. In effect this set of equations for a first order delay was repeated three times except that the total delay was divided evenly for each set of equations. Even though the total delay is the same, the response of the product completion rate, PC, to increases in the start-up rate, PB, will be futher delayed. This construction represents the assumption that changes in production rates are introduced by and initially experienced at the start-up rate and must then be passed on sequentially throughout the operation.

The finished product inventory equation is a simple accounting relation. The inventory at the computational instant equals the inventory at the beginning of the last computation interval plus what was received from manufacturing, PC, minus what was shipped to customers, PD, during the computation interval.

P3.K=P3.J+(DT)*(PC.JK-PD.JK) (11L)

P3 =(PC-PD)/s (12T)

P3 =PDAN*SAGA (13N)

P3 -- finished product inventory (units)
PC -- product completion rate (units/week)
PD -- product shipment rate (units/week)
PDAN-- steady state throughput (1000 units/week)
SAGA-- desired turnover time of
inventory (10 weeks)
DT -- Delta Time (0.5 weeks)
s -- Laplace frequency variable (radians/week)

The product shipment rate is used as the input device for all steady state and transient signals. A step input was used for most of the experiments of the transient responses of the systems because the step input is the summation of a series of input sine waves for all frequencies. Therefore, it will offer all frequencies in which to excite the system contol loops. Sine waves were introduced only to test the results of the frequency analysis and are therefore not represented here. Note the outflow is not restricted by the level of the inventory accumulation. A situation involving a negative inventory would represent the accumulation of backorders. Using this design enables the measurements of damping characteristics to be compatible for both stable and unstable systems.

PD.KL=PDAN+STEP(PDNS,PDNT) (14R)

PD =PDNS/s (15T)

PD =PDAN (I)

PD -- product shipment rate (units/week)
PDAN-- steady state throughput (1000 units/week)
PDNS-- amplitude of step input (100 units/wk)
PDNT-- time step input is initiated (5 wks)
s -- Laplace frequency variable (radians/week)

This completes the listing of equations included in the primary sector.

Secondary Sector

The secondary sector represents the production workforce and the information and decisional networks determining desired changes in the workforce. This sector includes the pressure signals that a production manager would create regarding his desired level for the workforce. Secondly it includes the response a personnel manager has toward these pressures in changing the workforce level. Finally it includes the workforce divided between production personnel and personnel in processing.

The flow in personnel in this sector was simplified to represent net changes within personnel levels. Therefore, hiring, firing, and attrition rates were represented by a single delayed dual directional flow. Inherent to this simplification is the assumption that only one of these activities is carried out at a time. This design simplifies feedback analysis by decreasing the number of control loops by two without decreasing the mathematical significance of the equations adjusting net employment levels. Once this system is clearly understood the two feedback loops controlling firing and attrition rates can be easily added without significantly altering the conclusions derived from this simplified model.

The workforce equation calculates the present accumulation of production employees as the addition of the last calculated value of production employees and the net change of production employees, SB, during the computation interval.

```
S2.K=S2.J+(DT)*(SB.JK)                                    (16L)
S2  =SB/s                                                 (17T)
S2  =PDAN/SACP                                            (18N)
```

```
S2   -- labor force (men)
SB   -- net change of labor force (men/week)
PDAN-- steady state throughput (1000 units/week)
SACP-- managements normal productivity
        attitude (5 units/man-week)
DT   -- Delta Time (0.5 weeks)
s    -- Laplace frequency variable (radians/week)
```

The employee processing delay represents the time delay of training new personnel and the time delay in completing arrangements to fire production personnel. For the simplicity of analysis this delay time was held constant regardless of the direction of flow through the processing delay. However, different delay times could easily be incorporated to corespond to the sign of the net personnel flow rate, SA. The two equations that represent this process delay make up a first order exponential material delay.

```
S1.K=S1.J+(DT)*(SA.JK-SB.JK)                              (19L)
S1  =(SA-SB)/s                                            (20T)
S1  =0 (men)                                              (21N)
SB.KL=S1.K/SBXD                                           (22R)
SB   =SA/(1+SBXD*s)                                       (23T)
SB   =0 (men/week)                                          (I)
```

```
S1   -- employee processing delay (men)
SA   -- net personnel change rate (men/week)
SB   -- net change of labor force (men/week)
SBXD-- employee processing delay time (weeks)
DT   -- Delta Time (0.5 weeks)
s    -- Laplace frequency variable (radians/week)
```

The net rate of change of personnel is comparable to an authorized rate of change of total personnel. It is the act of the personnel manager to increase or reduce the personnel level according to the pressures for adjustment that he receives from his superiors with consideration for adjustments already made. Included in the following equations representing the personnel manager's changes in the labor force, is a secondary adjustment time. This may signify the delay in finding suitable personnel for employment, or the delay and reluctance on the part of the manager to respond to the pressures to adjust the employment level. This adjustment time value is an essential part of the secondary managerial dynamic.

SA.KL=SAA.K+SAB.K	(24R)
SAA.K=(SAC-S2.K)/SAAA	(25A)
SAB.K=(-S1.K)/SAAB	(26A)
SA =(SAC-S2)/SAAA+(-S1)/SAAB	(27T)
SA =0 (men/week)	(I)

S1 -- employee processing delay (men)
S2 -- labor force (men)
SA -- net personnel change rate (men/week)
SAA -- authorized pressure from labor force error (men/week)
SAB -- pressure from employee process backlog error (men/week)
SAC -- desired labor force (men)
SAAA-- secondary manager's adjustment time (weeks)
SAAB-- secondary manager's in process backlog adjustment time (weeks)

The desired labor force is a pressure determined by taking the start-up rate desired by the production manager and dividing it by the productivity of the workforce. This productivity is held constant in these simulations but may be expanded to show causal behavior in productivity variations. This particular productivity would represent the management's attitude regarding employee productivity. The equation for the desired labor force is:

SAC.K=SAD.K/SACP	(28A)

SAC =SAD/SACP (29T)

SAC =200 (men) (30N)

SAC -- desired labor force (men)
SAD -- smoothed desired production start-up rate (units/week)
SACP-- managements normal productivity attitude (5 units/man-week)

The smoothed desired production start-up rate, SAD, is an exponentially weighted average of the pressure applied by the production manager to adjust the production capacity of the secondary. A long exponential time constant or averaging time represents a slow or patient perception on the part of the secondary manager to the system disturbances as related to him by the production manager. This reduces the amount of noise transmitted into the secondary system; however, it also decreases the responsiveness of the overall system. The equation is of the first order information delay type.

SAD.K-SAD.J+(DT/SADD)*(SAE.J-SAD.J) (30L)

SAD =SAE/(1+SADD*s) (31T)

SAD =PDAN (32N)

SAD -- smoothed desired production start-up rate (units/week)
SAE -- production managers desired start-up rate (units/week)
SADD--exponential averaging time (4 weeks)
PDAN-- steady state throughput (1000 units/week)
DT -- Delta Time (0.5 weeks)
s -- Laplace frequency variable (radians/week)

The production manager's desired start-up rate, SAE, is an adjusted summation of the desired production throughput, SAH; the perceived error in the primary inventory, SAF; and the perceived error in the in process backlog, SAM. This is the production manager's decision point for his policy input into the adjustment of the system. The adjustment times he applies to the errors in inventory and in process backlog reflect his patience in altering the system. Short adjustment times correspond to a manager's impatient desire for the system to respond to all disturbances. However, when the manager has a relatively impatient adjustment policy, the system tends to be unstable as disturbance signals tend to be amplified throughout the system. In this thesis is an examination of what comprises a relative level of impatience for different system design regions. The summation equation for the production manager's desired start-up rate is written:

SAE.K=SAF.K/SAFA+SAM.K/SAMA+SAH.K (33A)

SAE =SAF/SAFA+SAM/SAMA+SAH (34T)

SAE =1000 (units/week) (I)

SAE -- production managers desired start-up rate (units/week)
SAF -- perceived inventory error (units)
SAH -- average shipment rate or desired production throughput (units/week)
SAM -- perceived in process backlog error (units)
SAFA-- production manager's primary inventory adjustment time (weeks)
SAMA-- production manager's in process backlog adjustment time (weeks)

The calculations of perceived inventory and backlog error, SAF and SAM respectively, are made from simple comparisons of the perceived levels and the desired levels of the inventory and in process backlog.

SAF.K=SAG.K-P3D.K (35A)

SAF =SAG-P3D (36T)

SAM.K=SAN.K-P2D.K (37A)

SAM =SAN-P2D (38T)

SAF=SAM=0 (units) (I)

SAF -- perceived inventory error (units)
SAG -- desired inventory level (units)
P3D -- perceived inventory level (units)
SAM -- perceived in process backlog error (units)
SAN -- desired in process backlog level (units)
P2D -- perceived in process backlog level (units)

The desired levels of the primary inventory and the in process backlog are determined by their turnover times multiplied by the average throughput of the system. This is the simplest of forecasting techniques basing future preferences upon past performances. Other more sophisticated forecasting techniques may be employed but they would not necessarily add to the scope of this thesis.

A primary inventory turnover time should be in line with the goals of an organization. Considerations should include the ability of the inventory to service all customer needs, the ability of the inventory to buffer the production system from disturbances in a sales sector, and the cost of maintaining an inventory at a determined level. This thesis model does not distinguish between the different products that might be included in an inventory, nor does it consider the above conditions for determining the turnover time because these aspects do not significantly alter the dynamic responses of the system. An inventory turnover time was chosen large enough to maintain sufficient inventory (10 weeks) and allow a simple calculation of percentage changes within the inventory. Note the in process backlog turnover time is by definition equal to the delay time of unit processing, PCXD.

The equations for the desired levels of the primary inventory and in process backlog are:

```
SAG.K=SAH.K*SAGA                                        (39A)
SAG  =SAH*SAGA                                          (40T)
SAG  =PDAN*SAGA                                           (I)
SAN.K=SAH.K*PCXD                                        (41A)
SAN  =SAH*PCXD                                          (42T)
SAN  =PDAN*PCXD                                           (I)
```

```
SAG -- desired inventory level (units)
SAH -- average shipment rate or desired
         production throughput (units/week)
SAN -- desired in process backlog
         level (units)
SAGA-- desired turnover time of
         inventory (10 weeks)
PCXD-- process delay time (2 and 12 weeks)
PDAN-- steady state throughput (1000 units/week)
```

The final set of model equations represent the production manager's monitoring system of the shipment rate, the finished product inventory, and the in process backlog. These equations are first-order information delays which average exponentially weighted measurements of these three system variables. The exponential time constants or information delay times correspond to the delays of compiling measurements, normal accounting report periods, and the managerial time horizon used in viewing system state disturbances. Short delay times represent a continuous monitoring of system states and an emphasis on present state disturbances. Long delay times may include continuous monitoring in addition to a larger overall view of the system responses to external disturbances. These information delays act as information filters within the system averaging out high frequency disturbances to the system while decreasing the responsiveness of the system to such disturbances. The monitoring system equations include:

```
SAH.K=SAH.J+(DT/SAHD)*(PD.JK-SAH.J)        (43L)
SAH  =PD/(1+SAHD*s)                        (44T)
SAH  =PDAN                                 (45N)
P3D.K=P3D.J+(DT/SAHD)*(P3.J-P3D.J)         (46L)
P3D  =P3/(1+SAHD*s)                        (47T)
P3D  =PDAN*SAGA                            (48N)
P2D.K=P3D.J+(DT/SAHD)*(P2.J-P3D.J)         (49L)
P2D  =P2/(1+SAHD*s)                        (50T)
P2D  =PDAN*PCXD                            (51N)
```

```
P2D -- perceived in process backlog
         level (units)
P3D -- perceived inventory level (units)
P2  -- backlog of units in process (units)
P3  -- finished product inventory (units)
PD  -- product shipment rate (units/week)
PCXD-- process delay time (2 and 12 weeks)
PDAN-- steady state throughput (1000 units/week)
SAGA-- desired turnover time of
         inventory (10 weeks)
SAHD-- exponential information delay or
         averaging time (4 & 12 weeks)
DT  -- Delta Time (0.5 weeks)
s   -- Laplace frequency variable (radians/week)
```

This completes the derivation of the model equations for the primary/secondary control model in the context of a component of a production control system.

Financial Sector

The above equations complete the mathematical representation of the primary/secondary control system; however, a third sector, the financial sector, was added in order to provide some economic measurements of the impact of various changes to the system. This sector was not designed to demonstrate optimality for a specific set of system parameters. This would be inconsistent with the flexible hypothetical construction of this model; however, later this would enhance further applications of this model to specific systems. The measurements were simple representations of various accumulated costs inherent to a production system including employee wages, training costs, and severence wages. An expanded financial sector should include variable inventory costs, more elements of the training and severence costs, and the possibility of overtime pay instead of changes in employment levels. However, this sector was designed to give only a relative cost measure to the frequency and magnitudes of the changes within the employment sector to better understand the nonproductive costs of changing the employment level.

The equations of the financial sector and their descriptions are included in the model listing of Appendix B. It is important to emphasize that equations are not a part of the information feedback structure controlling the levels within the primary and secondary accumulations. An expanded model would possibly include financial pressures in as far as they alter management policies toward system monitoring and measurement and system adjustment times. Here the use of financial system measures for evaluating various system designs adds an external information loop for use in the model evaluation and comparison process that is the overview of this thesis or any study of simulated systems. Therefore, in this thesis, management policies are examined for their explicit causal contributions to system performances. Policies are not allowed to vary within a model simulation because of financial or other system pressures.

However, socioeconomic systems most likely do not have fixed management policies. Management policies may remain constant during normal ranges of operating conditions. But during periods of major conflict as previously described by Janis and Mann (10), managers often respond defectively in their decisional capacities. Future expansions to this model would include the organizational and financial relationships that vary management and employee policies toward the operation of the system. Policy changes might be experienced in the areas of system monitoring, system adjustment, management's attitude regarding employee productivity, and the employees' attitude regarding expected productivity. In the following chapters of this thesis the fixed levels of these policies will be discussed and evaluated.

Parameter Estimation

Finally, the model equations include many parameters that had to be given numerical values before a simulation could be made. Because of the hypothetical nature of this control system, parameter values have been chosen in order to demonstrate certain favorable and unfavorable dynamic response characteristics. Changing the constant values of the desired inventory turnover time, the employee productivity, the management productivity attitude, the steady state system throughput, and the magnitude of the step input do not significantly alter the system responses. Therefore, they were given values which helped only in the setting of the various scales of the system. On the other hand the values for the system's four decisional adjustment times, three information delay times, and two process delay times have considerable influence over the response characteristics of the system. The effects of changes in these parameters is a central issue in this systems analysis.

A repeated emphasis of the importance of a decisional adjustment time is not out of place. According to Fey and Low (14) the adjustment time "reflects the sensitivity of dynamic systems toward the attitudes of the decision maker who determines the loading under which a given system may operate. The adjustment time is an individual, very human kind of parameter which the real decision maker can vary rather readily" (p. 8).

Most likely few managers have thought about their adjustment time or their management time horizon, but these are mathematical representations of managerial attitudes. Conceptually they are determined by the time span over which a manager examines disturbances in his system and the quickness in which he seeks correction of system errors when he perceives errors exist. These concepts have been described as components of the managerial dynamic comprising a major portion of this systems analysis.

CHAPTER V

ANALYSIS RESULTS FOR A PRIMARY/SECONDARY CONTROL MODEL

The analysis of the primary/secondary control model notes the alterations in systems' responses caused by changing the values of the model parameters that define a system's managerial dynamic and specific design region. This corresponds to organizations or managers altering management policies to change the operating characteristics of their system and corresponds to different applications of this particular primary/secondary control structure. These observations include:

1. The effects and significance of establishing equal or different primary manager's inventory and backlog adjustment times.
2. The effects and significance of establishing equal or different secondary manager's adjustment times.
3. The necessary magnitude relationships between primary and secondary adjustment times inorder to maintain stability and strong control within the system.
4. The necessary magnitude relationships between primary and secondary adjustment times to control primary and secondary peak excursions.
5. The relationship between model stability and the ratio of the adjustment time magnitude to the total delay within its respective control loop.
6. The financial impact of system policy adjustments that influence system state control, stability and peak excursions.

These relationships are directed at the control of the model responses. The model responses are described in terms of damping characteristics, excursion magnitudes, and oscillation periods. While the manager is concerned with system states like inventory levels, production rates, sales rates, employment levels, hiring rates, productivities, and cash flows; a primary/secondary model's system of equations interrelates the manager's concerns, directs the system's controlled responses, and provides effectiveness measures for testing different managerial policies. An improved primary/secondary control structure as redesigned according to a specific organization's goals and objectives and the experimental results of the simmulations of the particular primary/secondary structure should offer a set of management policies that directs the adjustments of system states to compensate for a range of external disturbances while reducing the effects of the delayed systems responses deemed detrimental to the future realization of organizational goals and objectives. Therefore, a managerial dynamic is selected for a particular application of primary/secondary control in order to direct a desired internal response to a range of external disturbances.

A standard parameter set for this particular primary/secondary control structure was chosen for comparison of the responses of other altered primary/secondary systems. The dynamic operating characteristics of the standard primary/secondary control model were first observed. Tests upon alterations of the standard parameter set were conducted to determine parameter's statistical dominance. System response changes caused by the application of the primary/secondary control system in different design regions were observed. The frequency analysis demonstrated system sensitivity to different inputs, the amplification characteristics of the system, and the relationships between the model parameters and the different control loops. This integrated approach utilizing time, statistical, and frequency analysis techniques, provided a clearer understanding of the system's responses to transient inputs than is provided by just the analysis method of systems simmulation.

The Standard Parameter Set

The results of different model simulations, parameter dominance tests, and transfer function analyses were compared to the standard systems performance which is determined by the model structure and an initial set of model parameters. This parameter set defines the design region of the model as specified by the magnitudes of the five delay times within the primary inventory control loop. The four standard adjustment times of the primary and secondary sectors that determine system loading were also established by this parameter set. As previously declared in the development of the model equations, the parameter values for this standard set are:

SAFA	-- primary inventory adjustment time	20 weeks
SAMA	-- primary process adjustment time	20 weeks
SAAA	-- secondary accumulation adjustment time	8 weeks
SAAB	-- secondary process adjustment time	8 weeks
SAHD	-- information averaging time	4 weeks
SADD	-- pressure smoothing time	4 weeks
SBXD	-- secondary process delay time	12 weeks
PBVD	-- response delay time	4 weeks
PCXD	-- primary process delay time	12 weeks

For the standard simulation, both the set of primary adjustment times and the set of secondary adjustment times were held equal. The total loop delay of the primary inventory control loop for this design region is thirty-six weeks. The ratios of adjustment times to loop delays were less than 5:6 but greater than 5:9.

The standard system's performance is graphically simulated by the DYNAMO compiler in Figure 4 for a 10% step increase in the shipping rate, PD, from the primary inventory. The simulated values for the primary inventory (P3), secondary labor force (S2), secondary in process backlog (S1), the in process start-up rate (PB), and the unit shipping rate (PD) are labeled and scaled accordingly. From the plotted DYNAMO output, the attenuation of the primary inventory (P3) and the secondary labor force (S2) can be observed along with the approximate natural frequency of the system (corresponding to a period of 138 weeks or time units) and the relative magnitude of the first peak excursions of these variables.

Specific performance measurements of damping characteristics and peak excursions for key variables were recorded in the printed output of the DYNAMO simulations. These measurements were determined by a set of MACRO equations written for this model and included in the equation list of Appendix B. The damping characteristic used for the parameter dominance tests is defined as a variable's amplitude ratio between the second and first excursions. Ratio values of 1.2, 1.0, 0.5, and 0.1 correspond to unstable, undamped, moderately damped, and stongly damped

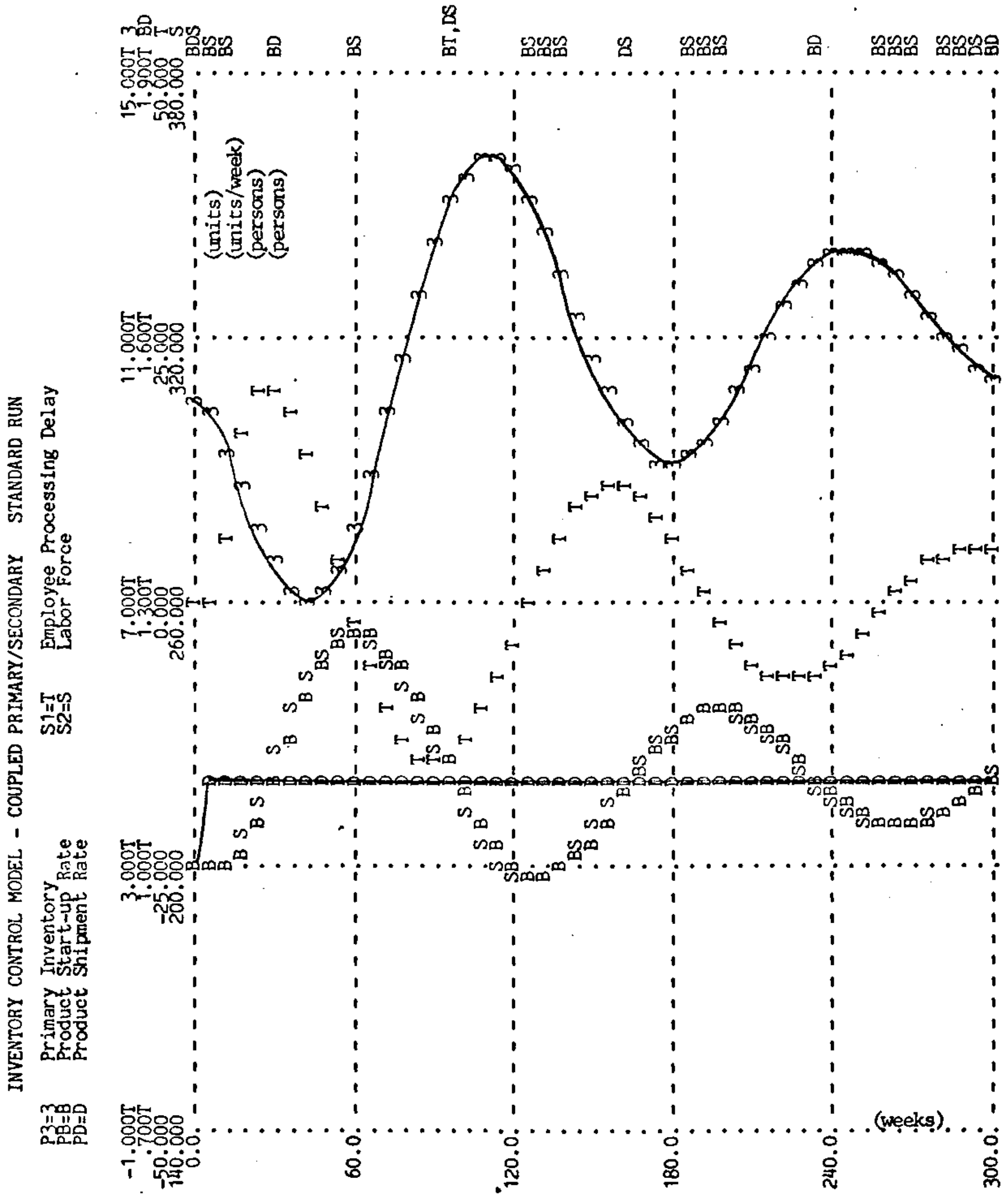

Figure 4. Standard Run of Primary/Secondary Model

system responses respectively. These are all cases of underdamped systems experiencing different degrees of overshoot and oscillation. Because critically damped and overdamped systems were not considered of interest, this measurement of damping provided a clearer and easier method of distinguishing the different degrees of system stability and system control as compared to the classical definition of the damping ratio which will be observed in the frequency analysis. The values of these system measures for the standard model are:

P3DAMP	-- primary inventory damping characteristic	0.482
P3EXC	-- primary inventory percentage change for first excursion	-29.34%
S2DAMP	-- secondary labor force damping characteristic	0.486
S2EXC	-- secondary labor force percentage change for first excursion	26.33%
T	-- period of system oscillations	138

The standard simulation is an example of a moderately controlled system as determined by the steady damping characteristics (0.482 and 0.486). The percentage magnitude of the first peak excursion in the secondary accumulation of 26.33% is less than the percentage magnitude of the first negative excursion for the primary inventory, -29.34%. While this is a moderate fluctuation in the system to compensate for the error caused by a 10% step increase in the primary outflow, it demonstrates that a percentage of the disturbance was absorbed by the primary inventory and therefore, was not passed on to the secondary sector. This buffering of one sector by another sector is normally discussed with respect to the steady state operation of a control system involving amplification of sine wave input signals. However, in discussing this model in context with the possible goals of a system, this transient response for each sector relative to buffering potential, is an important measure of the acceptability of a system design.

System goals contain policies regarding acceptable inventory and production levels. Inventories are maintained to allow flexibility in production schedules while making available a company's full product line. This buffer between product sales and production scheduling made available by the inventory, improves the overall efficiency of a manufacturing operation. There is less need for the frequent scheduling of the production of a particular product. However, the costs incurred in maintaining an inventory help establish a policy regarding the maximum dollar value allowed to be tied up in inventories. Therefore, in an application of this control model, acceptable maximum and minimum inventory levels would be established in order to evaluate the different system responses.

The attitudes regarding employment security and maximum and minimum production levels as determined by employment levels and productivities, would also enter into the overall set of management policies used to evaluate the various system parameter sets. Many organizations find it to their advantage to develop a more stable workforce. Other organizations find it necessary to immediately respond to sales disturbances inorder to maintain and develop their market position or minimize inventory requirements. The first organization might be more prone to accept greater fluctuations in their inventories or employee productivity in order to stabilize their minimum employment levels. The second organization might have a very responsive employment sector in order to quickly adjust production and inventory errors.

The inclusion of variable productivities in the primary/secondary control system would help decrease the necessity to make such large adjustments within the secondary sector. However, additional costs are incurred because of the slack built into the system and the possible necessity to pay overtime wages to increase productivity. For most of these analyses of the primary/secondary control system, productivity is held constant in order to more clearly evaluate the response characteristics determined by the system adjustment times and the model design regions. Variable productivities were briefly examined to demonstrate the above mentioned changes in response characteristics.

The above considerations and observations are developed by the integrated feedback dynamics methodology of the primary/secondary control structure. A statistical analysis of the DYNAMO output data is completed to determine the statistical dominance of certain model parameters in controlling the system's dynamic response. This statistical experimentation is first carried out for the standard parameter design region. The results are then examined with respect to other design regions in order to test the general applicability of the experimental conclusions. DYNAMO output data is also used to help demonstrate through the use of isocurves, some of the more significant parameter relationships of this control system. A system frequency analysis is carried out to examine specific relationships between the parameters and the system control loops and also determine certain measures of the sensitivity of the system to different input frequencies. Finally, certain alterations are made to the structure of this examined control model in order to better understand the implications of this analysis to the implementation of this control structure within a larger management environment.

Tests of Parameter Dominance

To better understand the relationships between the model parameters and the dependent system measures -- damping ratios, peak excursions, oscillation period, and financial measures -- a statistical analysis of the DYNAMO output data was completed. For these tests, certain parameters of the standard parameter set were altered (±25%) to determine statistical dominance. The financial measurements not previously identified included:

F2 -- cummulative personnel related costs
F2A -- cummulative payroll expenses
F2B -- cummulative personnel processing expenses

Test of Seven Model Parameters

The first test included an orthogonally arranged set of parameter alterations for seven of the model parameters. Nine model simulations were completed including a standard run and the eight orthogonally arranged reruns. Table 1 shows the arrangement of independent model parameters used for the nine runs of this test. Different tests include some of these parameters arranged in their same positions. Unaltered

Table 1. Orthogonal Arrangement of Model Parameters

RUN	SAAA	SAFA	SAMA	SAAB	PCXD	SBXD	SAHD
0	8	20	20	8	12	12	4
1	6	15	15	10	15	15	3
2	10	15	15	6	9	15	5
3	6	25	15	6	15	9	5
4	10	25	15	10	9	9	3
5	6	15	25	10	9	9	5
6	10	15	25	6	15	9	3
7	6	25	25	6	9	15	3
8	10	25	25	10	15	15	5

parameters were replaced by a 0, -1, or +1 as orthogonally appropriate to designate any interaction between remaining parameters. Information averaging time, SAHD, is used as a means to alter the total information delay within a loop $\pm 25\%$. Changing SAHD 25% changed the information delay times of SADD and PBVD 25%, thereby altering the total 12 week information delay by 25%. Listed in Appendix C is the parameter set and simulation output data for each model simulation. Listed in Appendix D for each statistical experiment is the sign and percentage of influence associated with each model parameter for each dependent system measure.

Stepwise linear regression applied to the output data of the DYNAMO simulations supplied the parameter coefficients of the linear regression models for the dependent system measures. Measures of the significance of the regression models, F statistics, and the significance of the individual coefficients themselves, t statistics, were also given. The parameter coefficients and the regression models were not accepted as significant if they were not significant to less than 0.05. Therefore, not all the input parameters are included in the regression models in order to preserve the accuracy of these linear approximations to the dependent measures of the simulated systems.

The stepwise regressions also supplied this analysis with measures of the percentage of explained variation of the dependent variables attributed to each parameter in the regression equation. As previously stated this is the measure of parameter dominance of that dependent variable. The direction of parameter influence of the variation in the dependent variable is determined by the sign of the parameter coefficient in the regression equation. The magnitude of the dependent variable alteration will be determined by the parameter coefficient multiplied by each unit change in the independent parameter.

The parameter influence diagram of Figure 5 helps summarize the statistical results of the first test. The percentage contribution to the explained variation of a dependent system measure and the sign of the influence is shown for each significant parameter on an influence vector toward the dependent system measures -- P3DAMP, P3EXC, S2DAMP, S2EXC, F2, F2A, AND F2B.

The production manager's inventory adjustment time, SAFA, is shown in Figure 5 to be significantly dominant in inversely influencing P3DAMP, S2DAMP, S2EXC, F2, and F2B. The responsiveness of the secondary sector, as determined by the magnitude of the secondary manager's adjustment time, SAAA, and the delay in the primary control loop associated with SAHD, are statistically significant in restraining primary excursion, P3EXC. However, the dominance of the production manager's adjustment time, SAFA, in determining the initial loading of the system including the control of the secondary sector responses (S2DAMP AND S2EXC) demonstrates the importance of this managerial policy. Patience applied within this position to the adjustment of the primary inventory should be a policy guideline for adjusting the load on the whole system. On the other hand, the quick response of the secondary manager reduces the drain upon the inventory caused by the step increase and allows the primary manager to reduce the pressure applied to the control system.

The cost of processing personnel, F2B, was significantly influenced by only the primary adjustment time, SAFA. The cummulative payroll expense, F2A, was shown to be significantly influenced by the information delay time, SAHD, more causally determined as a phenomenon of the period of the system operation which is strongly determined by the delays in the control loops. However, the variations in F2A are approximately 25% of the variations in F2B and the overall system costs,

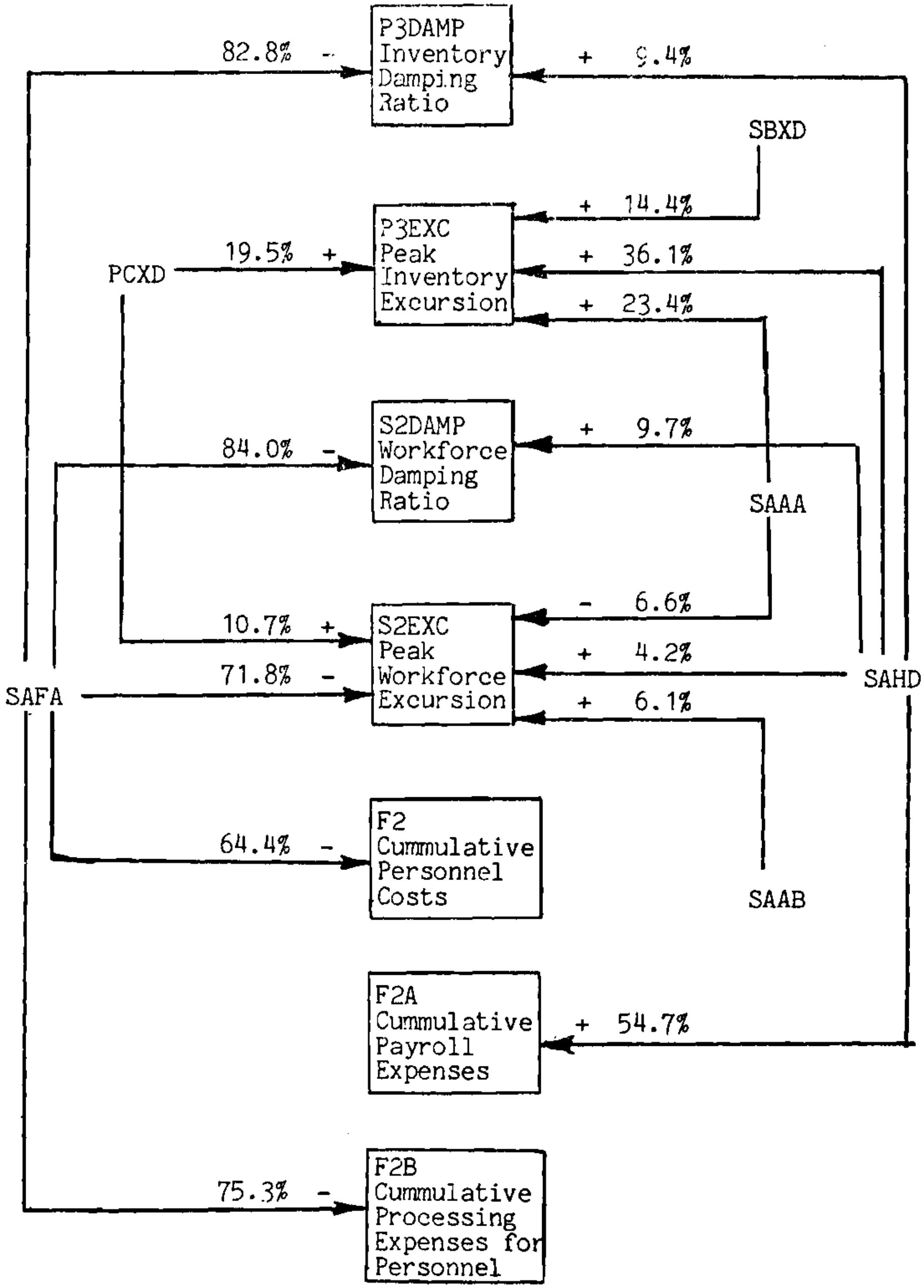

Figure 5. Influence Diagram for Seven Standard Set Parameters

F2. This is the reason F2 variations are closely related to those variations of F2B and significantly dominated by the same changes in SAFA.

Test of Six Model Parameters

Because of this overall dominance on the part of the production manager's adjustment time, a second test was made without alterations to SAFA in order to test the influences of the other six parameters. The parameter values for SAFA were replaced by the appropriate 0, +1, or -1 in order to see if any interaction between PCXD and SAHD helped strengthen the dominance of SAFA. The parameter influence diagram of Figure 6 summarizes these results. As anticipated, already established parameter influences were strengthened as new influences were demonstrated. Without the inverse control of SAFA upon the primary damping characteristic, P3DAMP, the proportional influences to P3DAMP of the backlog adjustment time, SAMA, and the secondary adjustment time, SAAA, demonstrate the need for less patience exhibited in these control policies. Other new influences show that the information delay, SAHD, is nearly twice as significant as the production delay, PCXD, and the secondary process delay, SBXD, in changing the primary inventory excursion and the secondary damping characteristic, P3EXC and S2DAMP. Therefore, twice as much system improvement will come from reductions in organizational methods of information handling or management policies regarding the time horizons for information averaging as compared to equivalent reductions in either process delay. Also as anticipated, decreases in the process delay of the secondary sector, SBXD, is shown to be very important in decreasing the cost of employee processing, F2B, and therefore overall system costs, F2.

In comparing Figure 6 to Figure 5 it is of greater importance to note that SAFA so clearly dominates the financial measures of F2B and F2 along with the dominance of the operational measures P3DAMP, S2DAMP, and S2EXC. Reductions in the overall loading of the system by increasing SAFA are more significant to the desired operation of the control system. Alterations in other parameters must be many times greater than the percentage alterations of SAFA before they cause a significant

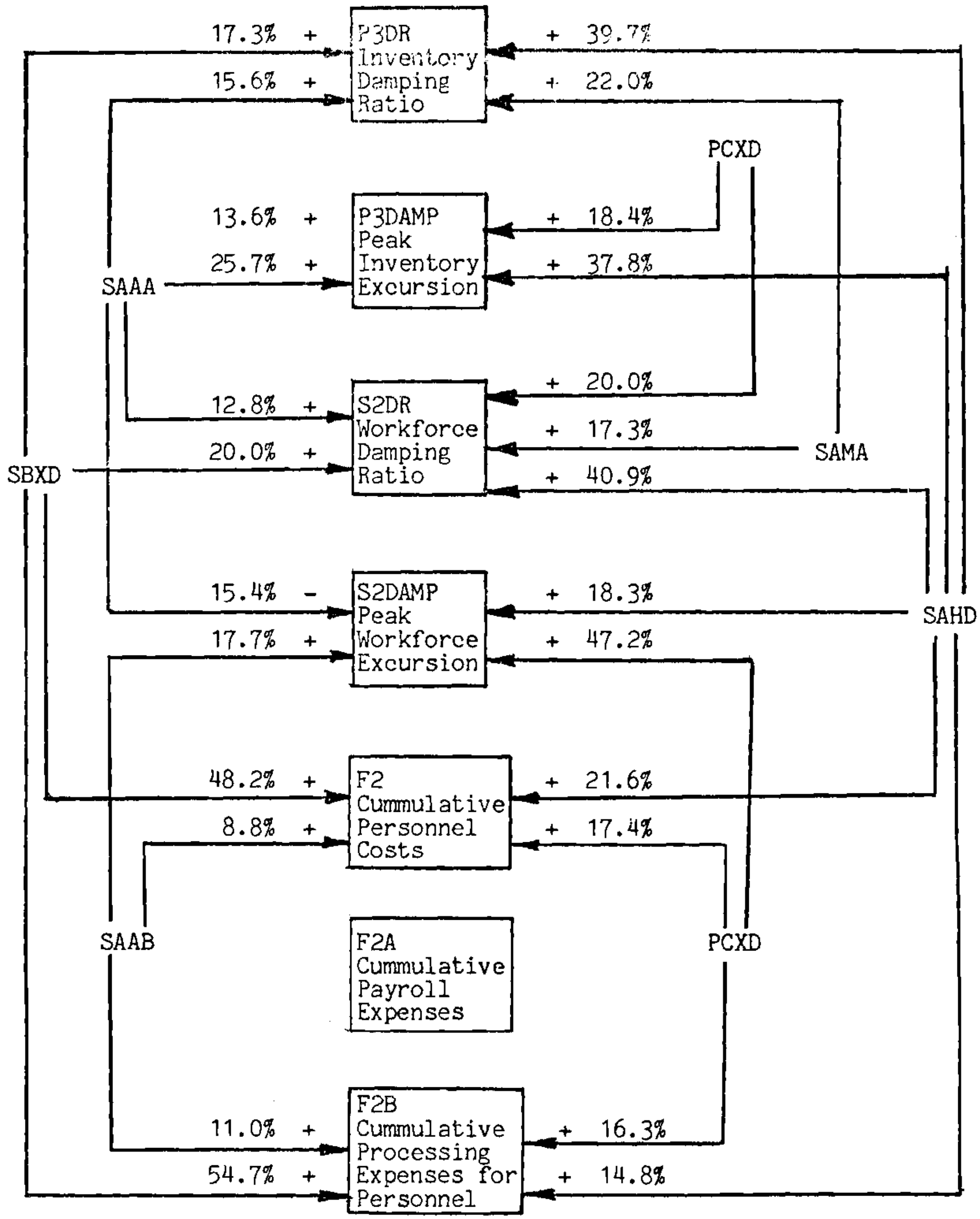

Figure 6. Influence Diagram for Six Standard Set Parameters

change in system's response.

Test of Three Model Parameters

A third and fourth test were prepared to examine changes in parameter influences when only the model adjustment times were altered. In addition to the dominance of SAFA being increased in the third test, the small influences of the backlog adjustment time, SAMA, and the two secondary adjustment times, SAAA and SAAB, were also more apparent. To emphasize these influences, the fourth test included only the alterations to the three adjustment times SAMA, SAAA, and SAAB. The results of the fourth test are summarized in Figure 7.

The fourth test demonstrates that patience is not always the prescribed policy for system control. The purposes of the in process backlog control loop include correcting any deficiencies within the desired production rate and resisting any tendencies on the part of the inventory adjustments to overcorrect the system. This control loop becomes more influential in controlling P3DAMP, S2DAMP, F2, and F2B as the production manager exhibits less patience in his backlog adjustment time than in his primary adjustment time. Shorter backlog adjustment times initially increase the responsiveness in the earlier part of the transient response period before finally resisting the tendency to overcorrect the system in the latter transient period. This latter transient period is the time between the initial correction of the in process backlog and the initial correction of the primary inventory.

The inverse relationship between a sector's two adjustment times and their influences upon the dynamic responses of the system, are also seen in the control of the secondary sector's peak excursion , S2EXC, by the secondary accumulation and secondary process adjustment times, SAAA and SAAB. Again the secondary process adjustment time, SAAB, is compensating for attempts to overcorrect the secondary. As shown in Figure 7, it is more desirable to reduce S2EXC by reducing SAAB because of the additional side effect of reducing the cummulative costs, F2B and F2. Maintaining a relative impatience in the secondary adjustment time, SAAA, only increases S2EXC with half the reduction caused by SAAB while significantly reducing the primary excursion, P3EXC. This in turn, has

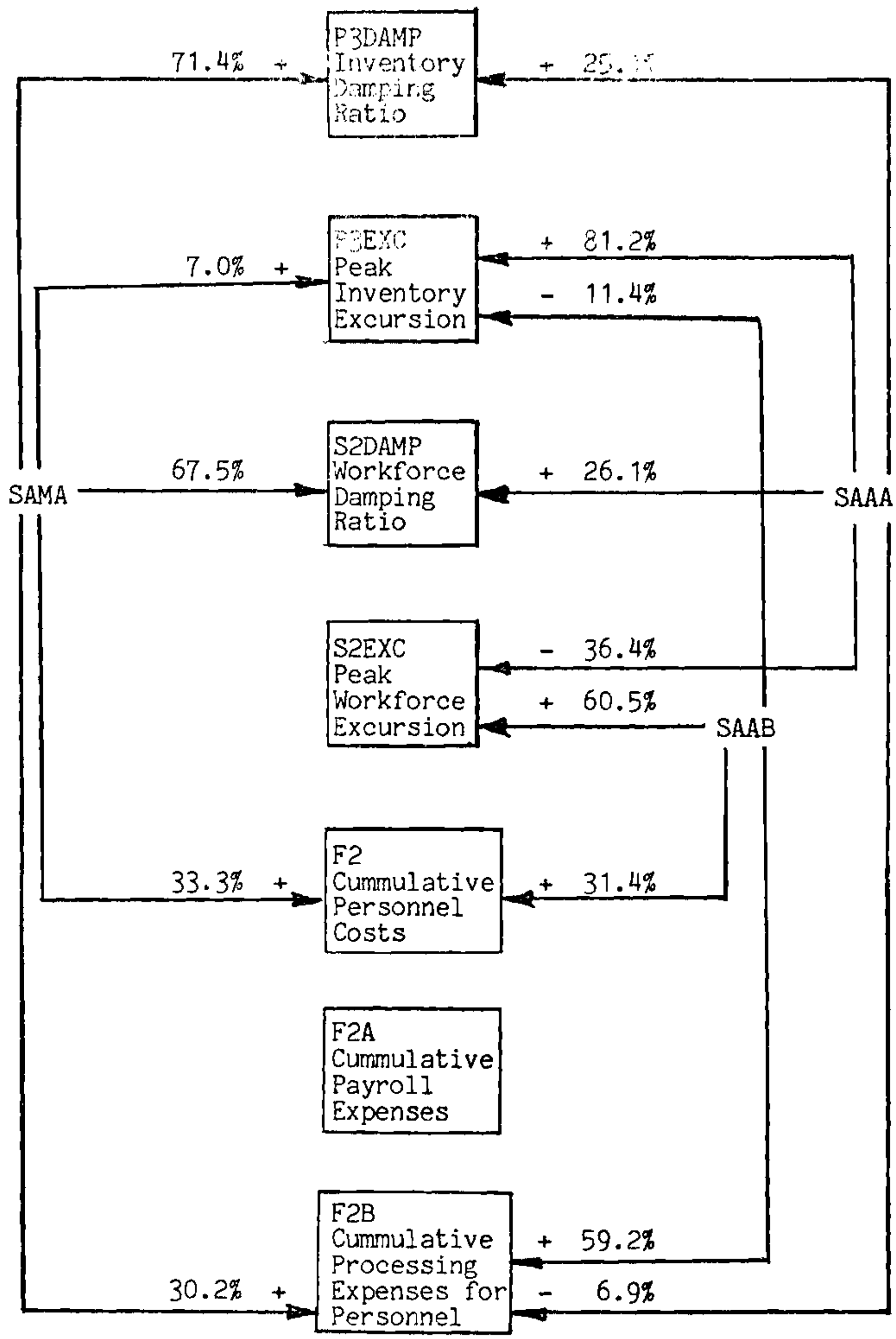

Figure 7. Influence Diagram for Three Standard Set Parameters

a greater effect upon the reduction of primary sector errors and therefore a reduction of the loading upon the control system by the primary adjustments.

This completes the description of the statistical analysis of the model simmulations utilizing the standard parameter set. For the standard parameter set, the primary adjustment time is the dominant control parameter in establishing the load placed upon the control system. Because of this inverse dominance it is important that managers exhibit patience in their adjustments to correct errors in the inventory accumulation. A shorter in process backlog adjustment time helps strengthen initial corrections of the in process throughput before compensating for the attempts of the primary control loop to overcorrect the system. It is desirable to have a relatively impatient policy of adjustment in the case of both secondary adjustment times. The secondary accumulation adjustment time, SAAA, predominantly influences the peak excursion of the primary accumulation, P3EXC, in a direct manner; however, it also inversely affects the accumulated costs of the system. The secondary process accumulation, SAAB, has an even stronger direct influence on the accumulated costs to the system while making sure overcorrection of the secondary sector does not take place. The 25% alterations to the three system delay times -- SAHD, SBXD, and PCXD -- in the first and second tests showed that the information delay time, SAHD, had a minor but statistically significant influence upon the system damping characteristics and excursion magnitudes. However, the real significance of these delays is more apparent in the tests of different design regions.

Tests of Parameter Design Regions

Changing the lengths of the delay times of the primary/secondary control model, allows the model to represent a different control region. A control region would represent a different application of the control model. Investigation of different control regions enables a more thorough development of the general and specific conclusions regarding primary secondary control. It is important to re-emphasize that even though the standard time units are in wee throughout this discussion, the units of time are significant only to the determination of the magnitudes of the parameters used. The magnitude relationships between the parameter adjustment times and the model delay times are the relationships that must be maintained if time units are switched for different control applications. Therefore, process and delay times could be in days or months while unit flow rates could be in units/day or units/month depending upon the application. Accumulation levels, flow rates, and conversion parameters would also have to be at their appropriate magnitudes.

For these tests of different design regions, the information delay, SAHD, the primary process delay time, PCXD, and the secondary process delay time, SBXD, were adjusted for six different design regions. the information delays, SADD and PBVD, were left unaltered for these tests. The magnitudes of the delays and the magnitudes of the standard adjustment times are shown in Table 2. Note the adjustment times used in order to have moderate control of the system. The ratios of SAFA to the total loop delay are all less than one while the ratios of SAAA to the secondary process delay, SBXD, are between 2:3 and 4:1. The simulation results of these region tests are shown in Appendix C and the numerical results of the statistical tests of these regions are summarized in Appendix D.

Because of the dominance of the primary adjustment time, SAFA, the greatest difference in the different design regions is the minimum SAFA necessary to maintain stability within the operation of the system. Throughout all the design regions, SAFA still inversely dominates P3DAMP, S2DAMP, S2EXC, F2, and F2B. However, in the first and second regions, SAFA also directly influences the primary inventory excursion, P3EXC. In a primary control system this would be expected. Therefore, as the total loop delays are reduced, this system begins to more closely approximate the response of a primary control system with higher order information delays. The use of a secondary control sector with

Table 2. Parameter Design Regions Examined

Design Region	Standard Adjustment Times				Regionally Defined Delay Times					Total Loop Delay
	SAFA	SAMA	SAAA	SAAB	PCXD	SBXD	SAHD	SADD	PBVD	
1a	14	14	2	2	2	2	4	4	4	16
1b	14	14	8	8	2	2	4	4	4	16
2a	20	20	2	2	2	2	12	4	4	24
2b	20	20	8	8	2	2	12	4	4	24
3a	20	20	2	2	12	2	12	4	4	34
3b	20	20	8	8	12	2	12	4	4	34
4a	28	28	8	8	2	12	12	4	4	34
4b	28	28	16	16	2	12	12	4	4	34
5a *	20	20	8	8	12	12	4	4	4	36
5b	20	20	16	16	12	12	4	4	4	36
6a	28	28	8	8	12	12	12	4	4	44
6b	28	28	16	16	12	12	12	4	4	44

* standard model design region

relatively long adjustment times as compared to the secondary process delay times (second experimental case of the first, second, and fourth regions), adds to similarity between these models and a simple primary control model. The overdamped responses of these secondary control types are equivalent to the responses of first order exponential delays within primary control models. Therefore, to maintain the responsiveness of a primary/secondary control model, the secondary accumulation adjustment time must be relatively short as compared to the secondary process time.

The need for an increased responsiveness in the secondary was also exhibited in the regions where the primary process delay, PCXD, made up less than one-third of the primary loop delay (first second and fourth regions). In all regions it was determined to be desirable to have a responsive secondary sector to decrease the primary inventory excursions, P3EXC. But in the regions with the short primary process time, PCXD, the secondary adjustment time, SAAA, was statistically significant in its influence of the secondary damping characteristic, S2DAMP. This is the opposite response expected from a simple control loop like that of the secondary sector. However, it demonstrates the importance of a less controlled, highly responsive secondary to reduce the errors in the primary sector so that the dominant loading and influence to the secondary sector caused by the primary manager can be decreased as rapidly as possible.

This unexpected response characteristic is also seen in the reversal of the signs of influence that SAAA and SAAB have upon the accumulated system costs, F2 and F2B, for the first and second regions shown in Appendix D. As in the dominance tests of the standard model, these influences are relatively small as compared to the dominance of SAFA. But the signs of the influence are reversed. This signifies an improved response for the costs of system operation with a decrease in the secondary adjustment time, SAAA, and an increase in the secondary process adjustment time, SAAB. These two changes create a more responsive secondary for these two design regions.

The only other significant change in response characteristics concerns the influence of the primary process adjustment time, SAMA. As anticipated , the influence of SAMA is non existent in the regions where the process delay time, PCXD, is reduced from twelve to two weeks or reduced from approximately 35% of the total primary loop delay to less than 6% of this loop delay. Because of the smaller number of units in process, the magnitudes of the in process errors are insignificant in comparison to the errors in the primary inventory. Therefore, they are nearly neglected in the summation of adjusted errors which directs the desired changes within the secondary sector.

The results of these regional analyses help develop general and specific guidelines for the application of primary/secondary control. The primary inventory adjustment time , SAFA, is predominant in its influence of the control model but must be adjusted according to the overall delay time within the primary control loop. Extremely short values for the primary process delay time, PCXD, make the influence of the backlog adjustment time, SAMA, very insignificant. Also, very long values of the secondary adjustment time, SAAA, remove the oscillatory tendencies of the secondary sector while creating a very unresponsive control situation. The responsiveness of the secondary improves the overall response of the control system by reducing the excursions of the primary inventory and in some cases significantly reducing operating costs and secondary operating characteristics.

Graphic Summaries of Standard Design Regions

To further emphasize the influences of the system adjustment times and assist in possible design adjustments of this control structure, DYNAMO model simulation output data were used to plot isocurves for specific levels of system measurements against different primary and secondary adjustment times of the fifth or standard design region. The three curves in Figure 8 depict constant levels of system control (damping characteristics approximately equal to 1.00, 0.50, and 0.25) for different adjustment times. Two curves in Figure 9 were determined to distinguish necessary adjustment times for maximum 25% and 27% transient excursions in the secondary accumulation. Also in Figure 9 two more isocurves were developed to establish the adjustment times necessary to hold primary inventory transient excursions to less than 30% and 32%. The odd curve of both Figures 8 and 9 represents the necessary relationship of primary adjustment times to secondary adjustment times to insure transient buffering where percentage excursion magnitudes in the primary inventory are greater than or equal to the percentage excursions of the secondary accumulation. The data used to develop the isocurves of Figures 8 and 9 are recorded in Appendix E. This data can be easily and economically obtained by using the macro equations for the measurement of system damping characteristics and peak excursions that are included in the model equations of Appendix B and printed output data for only the first and last calculation times of a model simulation.

These isocurves help demonstrate the previously described parameter influences. It is shown in Figure 8 that increasing the primary adjustment times significantly reduces the overall damping characteristic of the model. However, greater percentage reductions must be made in the secondary adjustment times to reduce these same damping characteristics. This same relationship is even more apparent in the alteration of the secondary accumulation's transient excursions. In Figure 9 drastic increases or decreases in the secondary adjustment

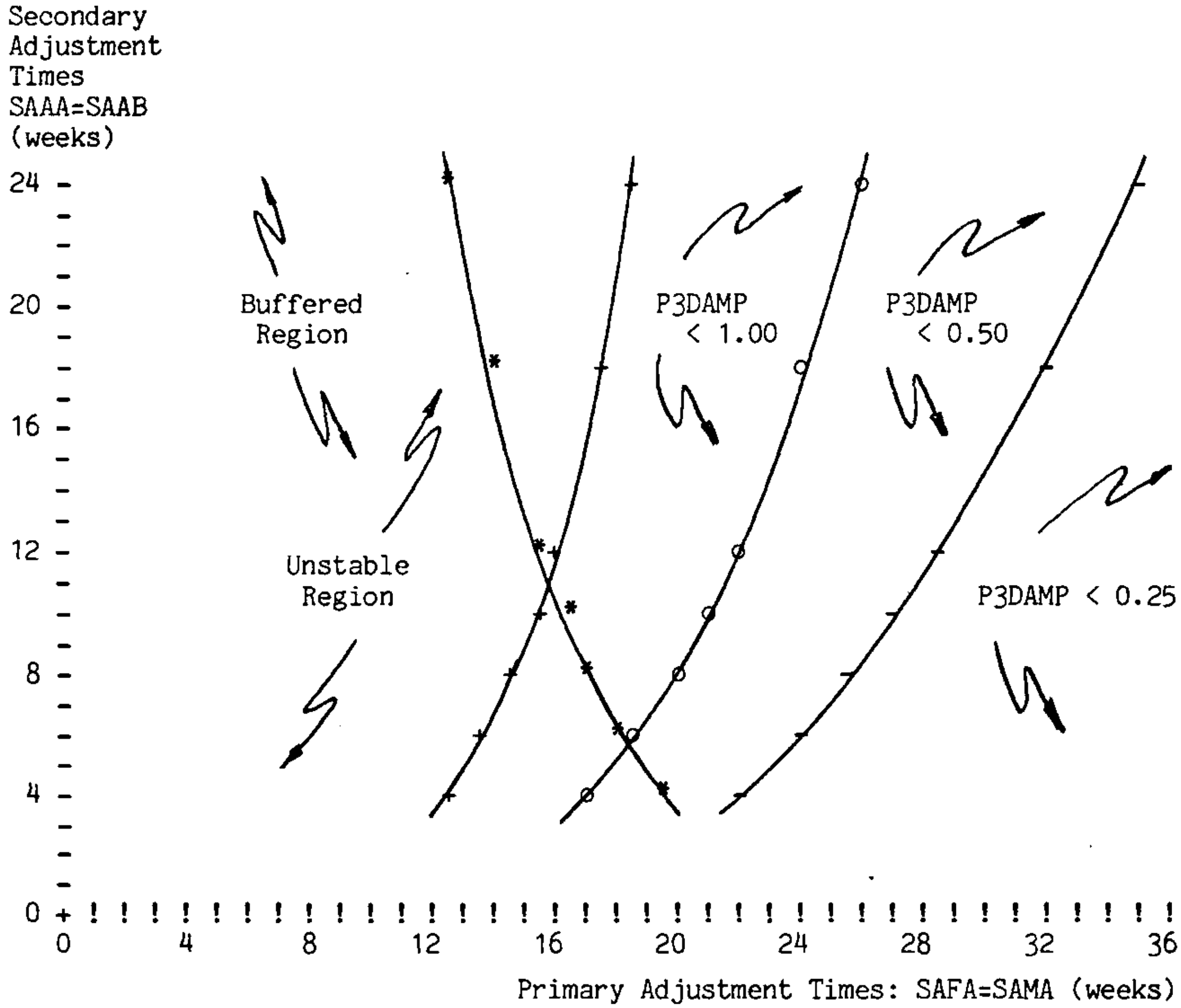

Figure 8. Isocurve for Primary Sector Damping Characteristic P3DAMP

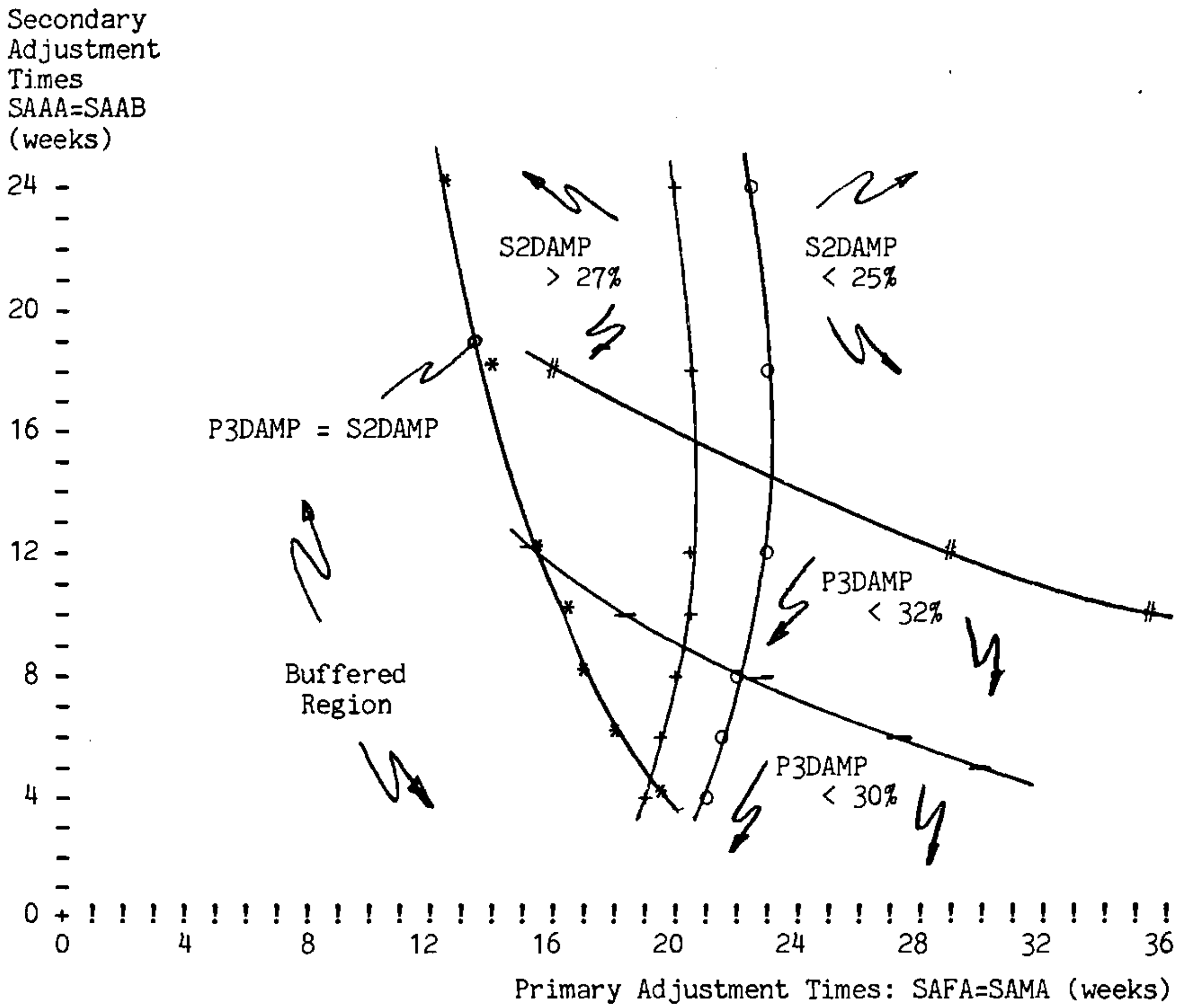

Figure 9. Isocurves for Excursions in Primary and Secondary Sectors

times cause relatively minor changes in the secondary accumulation's excursions. Conversely, small adjustments to SAFA and SAMA bring about significant changes in this system measure as seen in the comparison of isocurves for representing maximum 25% and 27% excursions in the secondary accumulation. The influence of the responsiveness of the secondary can be seen in the two curves representing maximum 30% and 32% excursions in the primary inventory. Major changes in the primary adjustment times are less effective as compared to minor changes in the secondary adjustment times. The odd curve of Figures 8 and 9 provides a further division of the parameter design sets into those involving buffered and nonbuffered transient excursions of the secondary accumulation.

To further understand the operating characteristics caused by responsive primary and secondary sectors and the parameters associated with them, a classical control theory frequency analysis was completed for the primary/secondary control model.

Frequency Analysis of the Primary/Secondary Control Model

The frequency analysis of the system determines the natural frequency and bandwidth of the system, the system gain, the high frequency cut off point, and the tendency of the system to continually oscillate, attenuate, or become unstable. The frequency analysis is performed mathematically by forming the system transfer function from the Laplace transforms of the linearized incremental equations which approximate the original nonlinear set of difference equations. Such a function relates the behavior of one variable to the behavior of any other. Usually the transfer relation between the input and the principal variable of interest is determined.

The mathematical expression for the transfer function between the input variable, product shipping rate (PD), and the principal variable of interest, primary inventory (P3), is developed and shown in Appendix F. The transfer function is in the form of a sixth order polynomial divided by a seventh order polynomial. Because of the order of the numerator and denominator of this transfer function, no closed form solutions may be determined and therefore standard frequency analysis determinations may not be made as literal functions of system parameters. However, utilizing numerical solution techniques on the level of the Newton-Bairstow method to solve for the poles of the transfer function and determining the magnitude of the transfer function as a function of randian frequency (w) will yield information valuable to a feedback dynamics analysis of a control model.

Poles of the System's Transfer Function

The roots of the seventh order denominator polynomial are the poles of the transfer function. The reduced form of the denominator of the transfer function had to be expanded in order to determine the coefficients of this seventh order polynomial. The DYNAMO compiler was used to calculate the polynomial coefficients. The model equations for the calculation of the coefficients of the denominator of the transfer function are presented in Appendix G. The roots of the polynomial were then determined by the numerical solution method of Newton and Bairstow. This numerical search procedure determined that for the standard model parameter set, there were three complex conjugate root pairs and one negative real root. An s-plane plot of these seven roots is shown in Figure 10 along with the plotted movements of these roots as directed by alterations to the primary adjustment times. In Figure 10 the three positive imaginary poles for the standard parameter set are designated by a circled "x". The positive roots of the first and second root pairs are shown seperately in Figures 11, 12, and 13 in order to more clearly show the effects of other parameter set alterations.

There are two system responses that may be obtained from these s-plane pole diagrams. The natural frequency of an associated pole pair is determined from the radian distance between the pole and the origin of the s-plane. This is calculated from the square root of the sum of the squares of the magnitude of the imaginary and real parts of a pole's position. The second important response is the classically defined damping ratio associated with a pole pair. This is the negative cosine

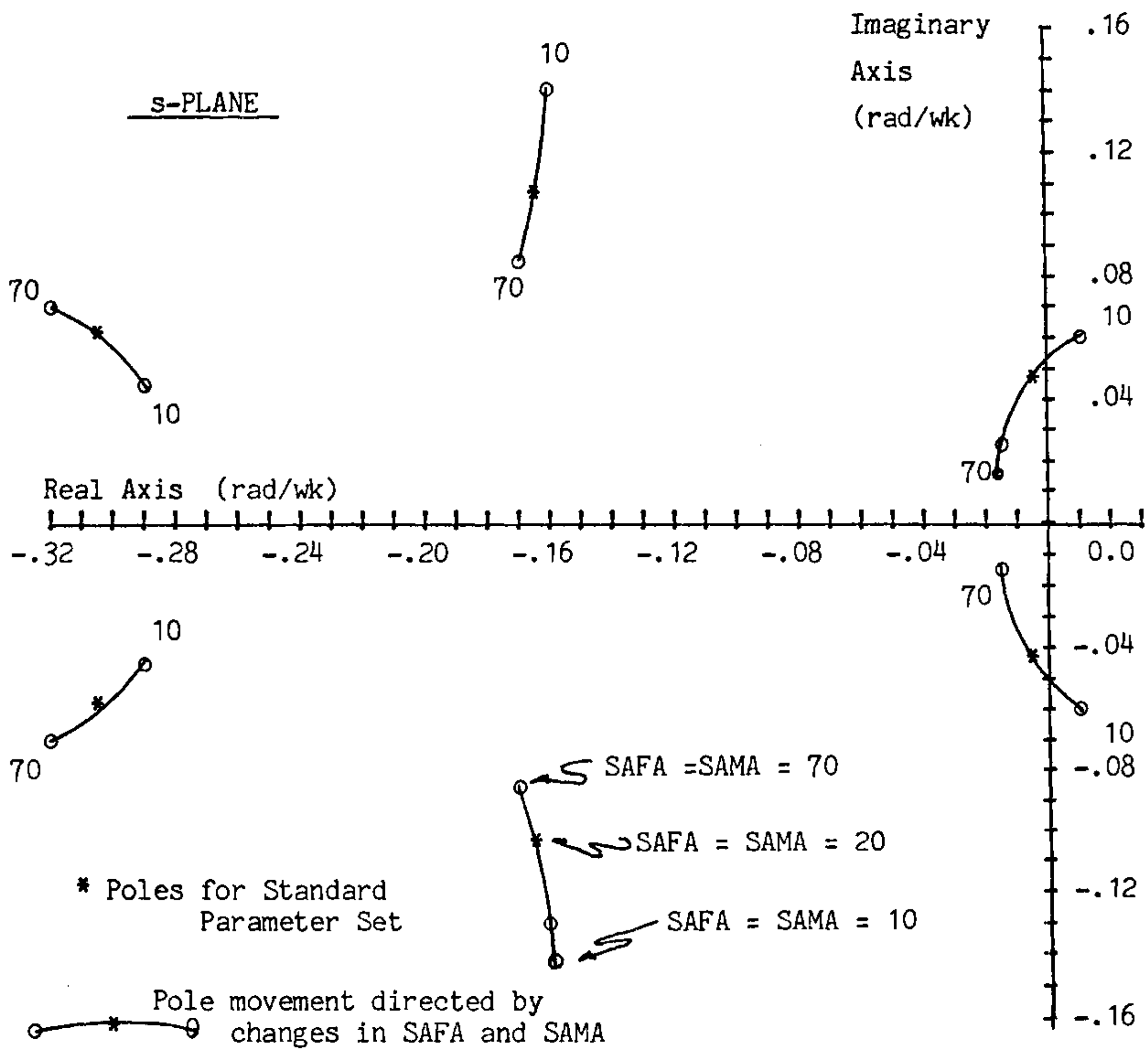

Figure 10. Poles of the Transferfunction P3/PD

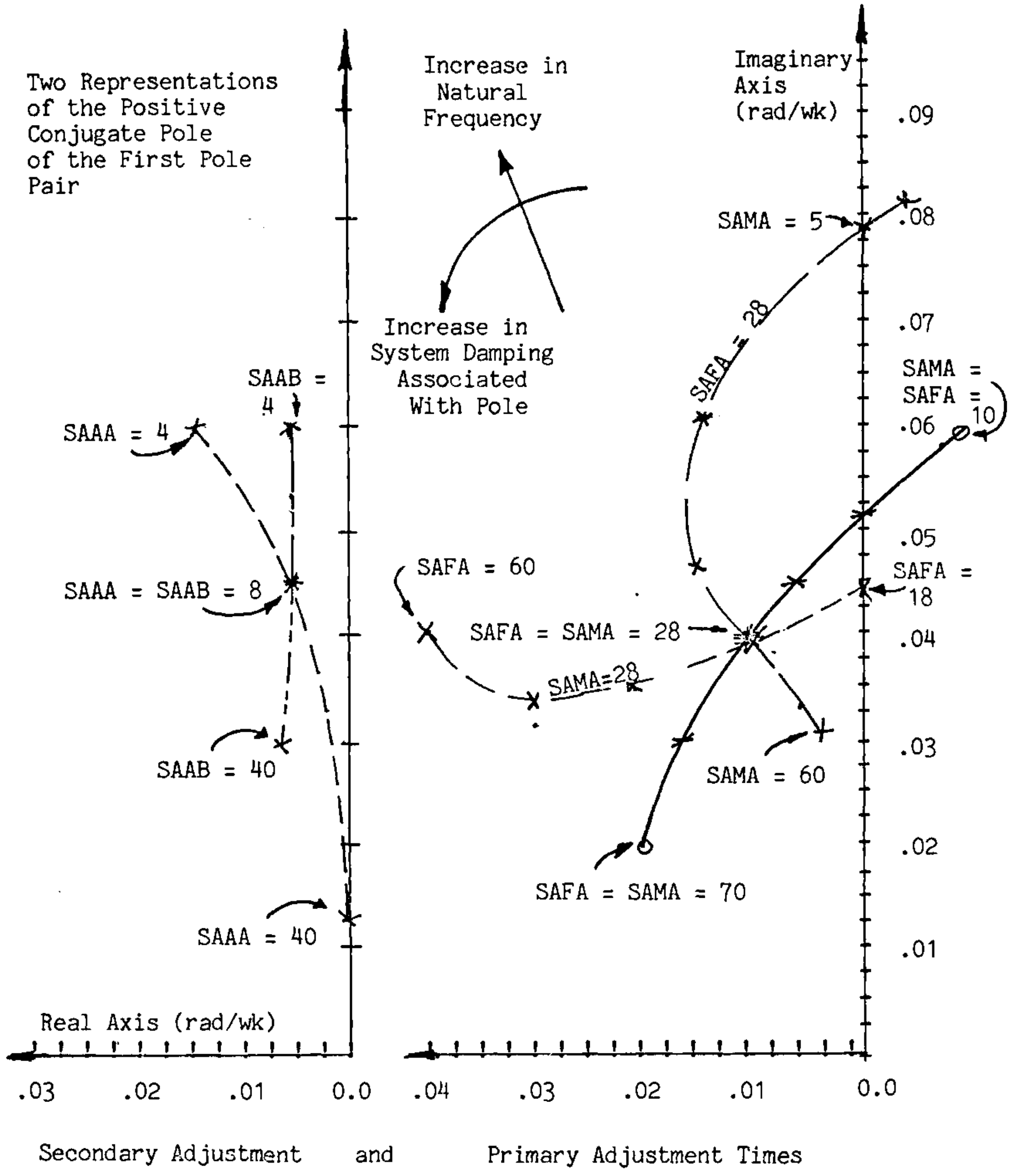

Figure 11. Parameter Adjusted Shifts in the position of the First Pole Pair

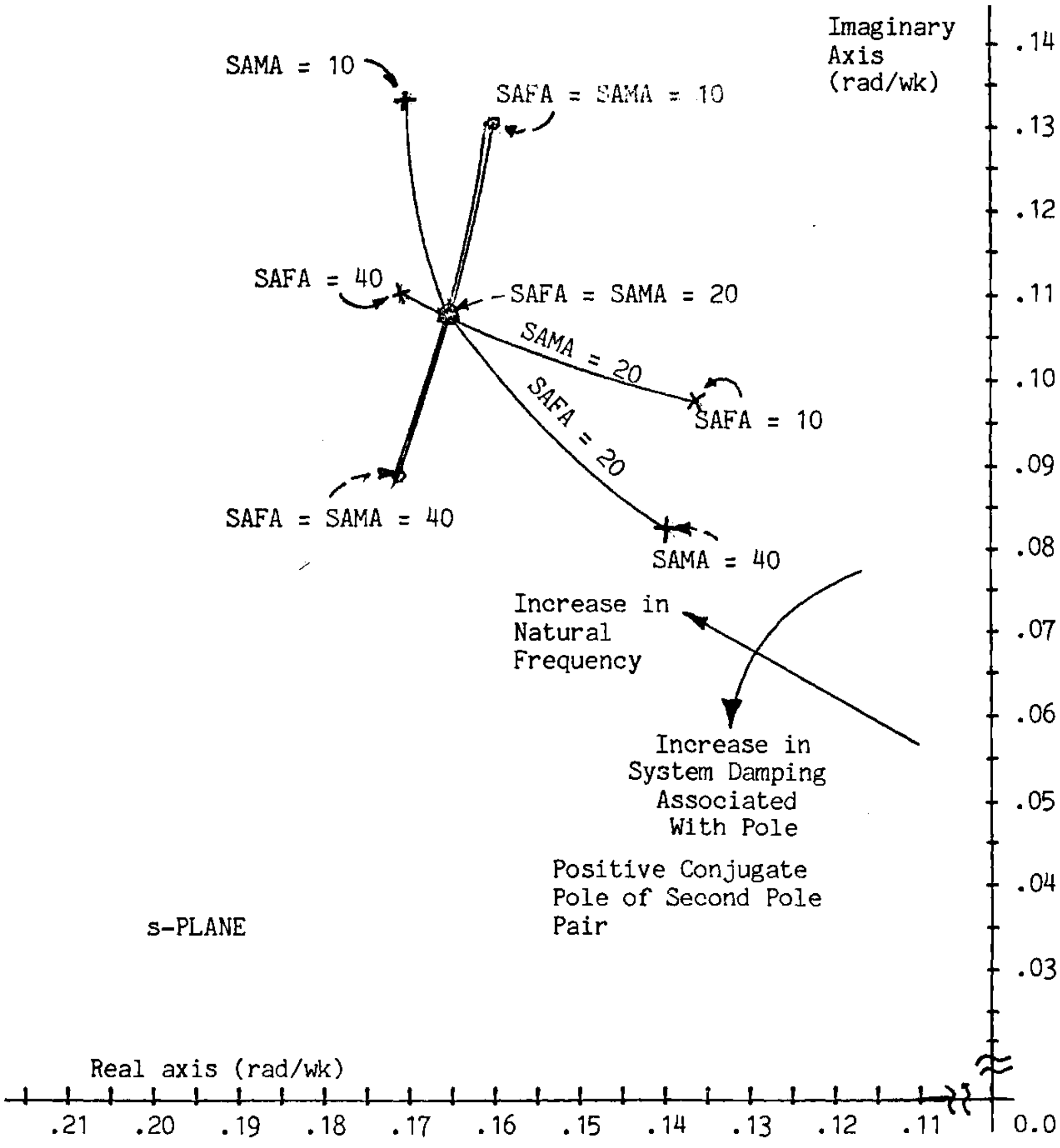

Figure 12. Primary Parameter Adjusted Shifts in the Position of the Second Pole Pair

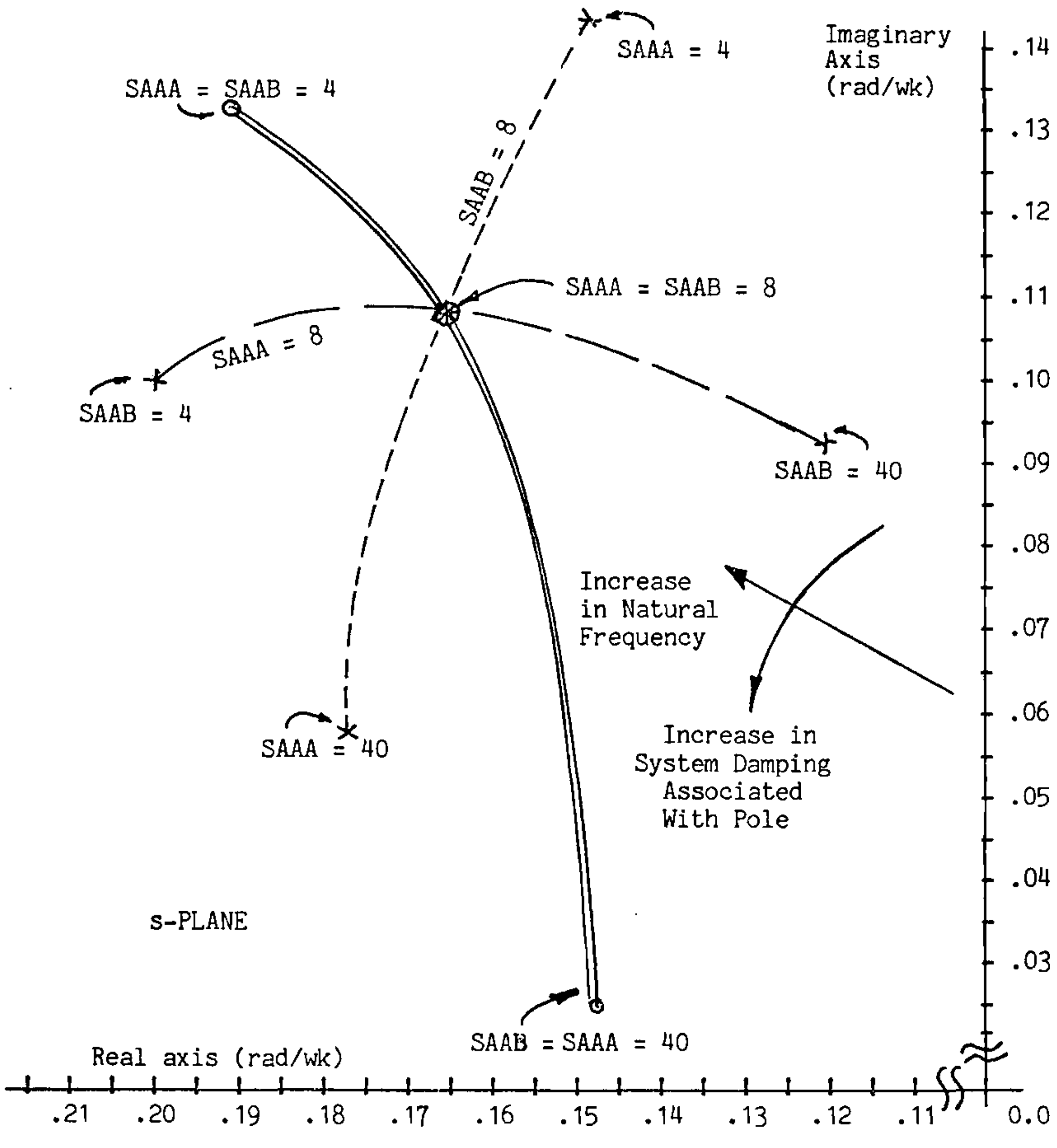

Figure 13. Secondary Parameter Adjusted Shifts in the Position of the Second Pole Pair

of the angle between the real axis and a line drawn from the origin to one of the poles of the pole pair. Therefore, poles close to the origin represent low frequency system responses while those poles farther from the origin represent high frequency system responses. And poles with small angular distances from the negative real axis represent strongly damped system responses (damping ratio > 0.80) while those with larger angular distances represent less damped (0.0 D.R. 0.80) or even unstable (D.R. 0.0) system responses. The pole pair with the least natural frequency and least associated damping characteristic should dominate the overall influence of the control system as the other responses associated with the other poles will be attenuated much earlier.

Tests upon the position of the first pole pair show that it is closely related to the overall operating characteristics of the model. For the standard test run, this pole pair corresponds to a moderately underdamped system (D.R. = 0.12) with a natural frequency of .0455 RADIANS/WEEK or a period of 138 weeks. As the test results show in Figure 11, the damping associated with this pole pair decreases as SAFA and SAMA equally decrease so that when they are approximately equal to 14 weeks the system becomes unstable. These results correspond to the simulation results for the standard run and the test for the region of system instability (Figure 8). Therefore, the pole position of this pole pair corresponds to the overall internal dynamics of the primary/secondary control system relative to the system natural frequency and damping characteristics.

Different parameter adjustments were made to test the shifts in different pole positions. The changes in the first pole pair coresponded to many of the changes in the overall system responses of the primary/secondary control structure, because the least natural frequency and damping ratio is associated with this pole pair. Decreases in the four adjustment times caused similar alterations in the natural frequency associated with both the first pole pair and the overall system natural frequency. The natural frequency was decreased by reductions in the secondary process adjustment time (SAAB) and increased by reductions in the primary adjustment time (SAFA), the primary backlog adjustment time (SAMA), and the secondary adjustment time (SAAA). Also, the damping characteristics associated with both the pole position and the operating system decreased for the réductions in SAFA and increased for the decreases in SAAA and specific decreases in SAMA. Because of the stronger damping and higher frequencies associated with the other pole pairs as seen in Figure 10, these other system frequency components have a shorter transient influence upon the response of the system.

The changes caused by the reductions in the primary adjustment times are not unlike the adjustment time effects in a direct primary control model. However, these tests show that as the primary backlog adjustment time is significantly reduced below the magnitude of the primary inventory adjustment time, the influence of this parameter reverses causing decreases in the system damping characteristics. This represents a change in the system function of the backlog control loop. It no longer compensates for the tendency of the control system to overcorrect the inventory. Instead, the primary focus of the total system's control is moved from the area of inventory control and placed upon the area of production throughput control. This establishes the inventory as a more effective buffer between unit sales and production. Further decreases in the backlog adjustment time cause the system disturbances to be less attenuated. This characteristic is comparable to the previously described system responses caused by reductions in the primary adjustment time. The point at which the dominance of control shifts from the inventory control loop to the backlog control loop is closely correlated with the ratios between the adjustment times and the total time delays within their respective control loops. The primary control loop with the smaller ratio is the more dominant of the two control loops. In Figure 11 the shift point for a particular test model with a primary inventory adjustment time (SAFA) equal to 28 weeks occurs when the primary backlog adjustment time (SAMA) is reduced beyond 18 weeks. The respective loop delays are 36 and 24 weeks for this standard design region, and therefore, the ratios are approximately equal (28:36

and 27:36 respectively). Shorter values for SAMA than 18 weeks mean less overall system damping as represented by the clockwise movement of the first pole plotted in Figure 11 for reduced values of SAMA.

Even though the first pole is more representative of the overall system response, further tests of pole shifts show certain system characteristics related to the other pole pairs. In Figure 12 the positive pole of the second pole pair is examined and seen to be closely related to the strongly damped high frequency responses expected from the control loops of the secondary sector. For the standard simulation, this second pole pair corresponds to a control loop with a strongly damped (D.R. = 0.839) relatively high frequency response (0.198 radians/week or a cycle period of 31.7 weeks). The control loop structure of the secondary sector is comparable to a direct primary control structure. Therefore, reductions in the secondary accumulation adjustment time, SAAA, cause decreases in the damping or increases in the responsiveness of the secondary sector while decreases in the secondary process adjustment time cause increases in the damping or decreases in the responsiveness of the secondary sector. However, this is the reverse effect that these adjustment times have upon the total system response which is best approximated by the position shifts of the first pole in Figure 11. The significance of this inverse system response phenomenon associated with this second pole pair is that it points out that to improve the overall response of the primary/secondary control system, it is necessary to increase the responsiveness of the secondary control sector.

As changes in the secondary adjustment times had moderate effects upon the alterations to the positions of the first pole pair, changes in the primary adjustment times had similar effects upon the alterations of the position of the second pole pair. In Figure 13 decreases in the primary adjustment time, SAFA, are seen to cause insignificant changes in the associated damping and natural frequency of the second pole pair. However, decreases in the backlog adjustment time, SAMA, are seen to cause moderate decreases in the associated damping and moderate increases in the associated natural frequency of the pole pair. This is most apparent when SAMA is given values less than those of SAFA. In these cases the model is more dominantly controlled by the higher frequency backlog control loop, and reductions in the backlog adjustment time will cause less higher frequency damping in both the total system and the primary sector loading of the secondary sector.

The third pole pair signifies a nearly critically damped high frequency component in the control model. For the standard parameter set the classical damping ratio equals 0.982 while the natural frequency is 0.198 radians/week and the cycle period is 19.8 weeks. Decreases in the values of the primary adjustment times only increase the natural frequency associated with this pole pair. Decreases in the secondary adjustment times also cause increases in the associated natural frequency. The changes in damping ratios caused by the variations of adjustment times are not significant this close to critical damping (0.97 to 0.99). This pole pair may signify a composit effect of the information and process delays of the system and the secondary process control loop. However, the pole pair adds little to the response of the overall system because of its characteristic damping and high frequency.

This root analysis of the system transfer function demonstrates certain response characteristics of the various control loops of the primary/secondary model. The first pole pair is closely related to the overall dynamic response of the system because of its lower associated natural frequency and damping ratio. Its position is significantly altered by the two primary adjustment parameters of the two primary control loops. Its position is also moderately altered by changes to the secondary adjustment parameters of the secondary control loops which are nested inside the primary control loops. This enables the response of the secondary sector to alter the responses of the primary control loops. This secondary sector response is characterized by the positions of the second pole pair. Changes to the secondary adjustment times to increase the responsiveness or oscillatory behavior of the secondary sector actually decrease the oscillations in the overall system response. The experiments upon the first and second pole pairs show that when the second pole pair is shifted by altering the secondary adjustment times to represent a more oscillatory secondary sector, the overall system response closely represented by the first pole pair is a characteristically more desirable, stonger attenuated, higher frequency response.

System Gain Characteristics

Amplification is the characteristic of systems which causes the system's response to a sine wave input to have a larger amplitude than the input. In general, the amount of amplification will be different for different input frequencies. The plot of the magnitude of the transfer function as a function of w or the plot of the ratio of the output amplitude divided by the input amplitude versus radian frequency (w) is called the gain curve. It is of interest to know what the size of the response will be at different frequencies because any arbitrary input is a summation of different frequency sinusoids. Therefore, if it is known that the input is predominantly made up of certain frequencies and the system exhibits high gain for those frequencies, the expected responses will be very large. Since the slope of the gain curve can be changed by altering system parameter values, it may be possible to reduce its sensitivity to the prevalent inputs.

The model equation form for the calculation of the transfer function as a function of the Laplace frequency variable, s, is presented in Appendix H. (Note for DYNAMO simulation of this gain curve the frequency variable, s, is replaced by the time variable TIME.K).

Three gain curves for different parameter sets are shown in Figure 14. Two parameter sets of the first region type were chosen for the first two curves to more clearly emphasize the information derived from this portion of a frequency analysis. The first curve represents a strong to moderately controlled system with a transient damping characteristic of 0.206. The second curve represents a very strongly controlled system with a transient damping characteristic of 0.056. However, the structure of this primary/secondary control model is sensitive to input sine waves with low frequencies or moderately long periods (between 50 and 130 weeks or time units). The first model gain curve is higher with a scaled peak of 5.28 when the input period, is

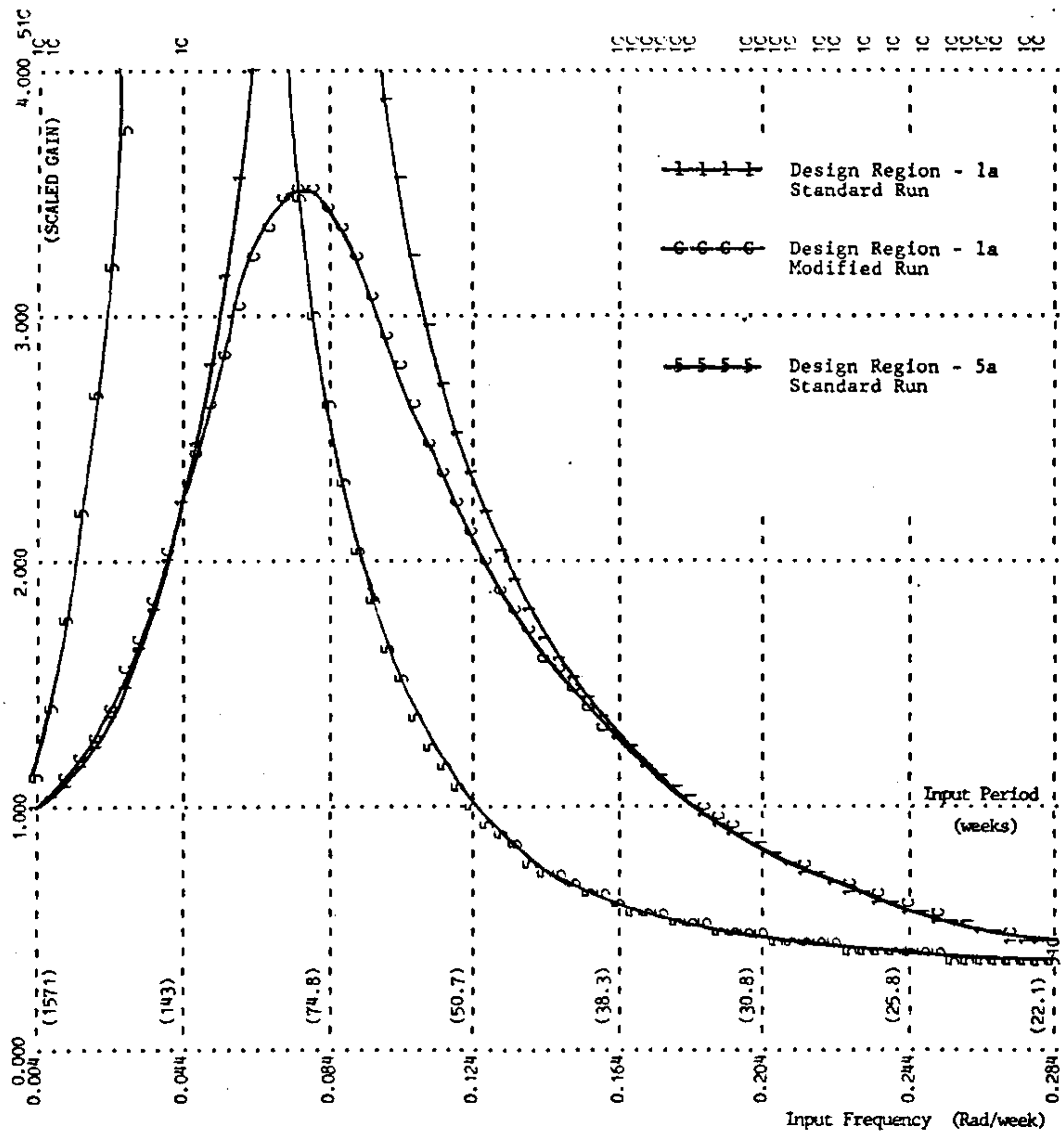

Figure 14. Scaled Gain Curve of the Transfer Function of the Primary/Secondary Control Model

78.5 weeks. The second model gain curve has a scaled value of 3.51 at that same input period, which is still considered high. This magnitude figure represents the amplification multiplier of the amplitude of a sine wave with a period of 78.5 weeks. Therefore, if an input sine wave with a period of 78.5 weeks had an amplitude causing a 10% variation in the normal outflow from this model, according to these two models the system inventory will fluctuate 52.8% and 35.1% respectively. This is not a desirable condition but characteristic of certain primary/secondary control models.

The third curve of Figure 14 is for the standard or fifth region parameter set. It exhibits a greater magnitude (11.5) at its peak frequency of 0.040 radians/week or a period of 157 weeks or time units. However, the given magnitude for a period of 78.5 weeks is 2.52, a more desirable amplification for this input frequency. It is also important to note that for input sine waves with periods of less than 50 weeks, this model attenuates the input signal while the other two models still have multipliers of 2.34 and 2.11 respectively. It can be said that model two is an inprovement over model one. However, model three is from a completely different parameter design region and may not be qualitatively related to the other two models but is only shown here to further describe the response characteristics of a primary/secondary control model.

A second inportant characteristic of the gain magnitudes of a control system is the sharpness of the peak of the gain curve. The higher and sharper the gain curve is, the more acutely the system is tuned to a small band of frequencies. The higher this sensitivity is, the more predictable the system's behavior will be toward certain input fluctuations. The control theory measure for sensitivity is called the Q of the system. Q is defined as the frequency of the gain peak divided by the bandwidth. The bandwidth is the width of the frequency range for which the gain curve is higher than .707 times the peak gain. Table 3 summarizes these values for the three curves of Figure 14.

These Q values are relatively low by engineering standards where the operating frequencies are much higher. However, they indicate a

Table 3. Three Examples of Model Bandwidth and Sensitivity

	Peak Frequency Rad/wk	Peak Magnitude (scaled)	Bandwidth Rad/wk	Bandwidth Input Periods	Q
Curve 1	.080	5.35	.039	62 to 101 wks	2.05
Curve C	.076	3.52	.061	57 to 126 wks	1.24
Curve 5	.040	11.51	.012	108 to 136 wks	3.33

fairly high degree of sensitivity for a socioeconomic system.

In many applications of a primary/secondary control system there exist many high frequency disturbances. Therefore, the ability of the system to reject such variations is of particular importance. A measure of this sensitivity is the cut-off frequency of the system. That is the frequency at which the gain becomes less than a specified value. Usually in engineering work, this value of gain is taken to be .707 times the value of the peak gain. At this point only half of the input power is reflected at the output. However, for this system this value coincides with many of the major disturbance frequencies experienced by a management control system (50 to 75 weeks). Therefore, another method of selecting a cut-off frequency is to ask what is the lowest noise frequency that interests the analyst or manager. If input disturbance periods of up to 26 weeks or time units are considered short term disturbances or system noise, the gain at this point would be of interest. The gains for these three curves are 0.572, 0.587, and 0.396 respectively. In all three cases these systems would moderately attenuate input signals with periods of less than 26 weeks and therefore, are not entirely sensitive to these frequencies.

From these primary/secondary control systems' gain functions, it would be expected that the systems would select from the inputs any powers at frequencies that fall within the 50 to 130 week period range, and amplify them substantially. It would also be expected that this response would persist throughout the steady state. The high frequency rejection for these control systems is moderate and therefore the systems will follow random disturbances to a much lesser degree.

Considerations for Apllication of the Primary/Secondary Control Model

The purpose of this investigation included the analysis of the response characteristics of a particular control structure relative to certain parameter configurations. This included understanding the relationships of these parameters to their conceptual counter parts in the managerial dynamic; however, the uses for this control structure do not exist independently of other management relationships. Therefore, before completing this analysis, it is necessary to emphasize the purposes for examining these response characteristics with respect to possible implementations within control environments.

Assumptions made in the analysis of this model included maintaining many model components at constant values in order to better understand the characteristics of the four control loops of the primary/secondary control model. This effectively removed the existence of certain alternative decision loops. The model components held constant included the employees' productivity and management's productivity attitude. Also elements of the managerial dynamic were held constant for each particular simulation including the managers' adjustment times and information time horizons in order to better understand the relationships of their relative magnitudes to system response characteristics. In addition the two primary adjustment times were held equal and the two secondary adjustment times were held equal for the standard run of each design region. This conceptually appears to give equal importance to inventory control as compared to production control and equal importance to employment level control as compared to employment processing control; however, as shown in the root analysis this is conceptually wrong. Other possible restrictions caused by raw material shortages, skilled labor shortages, and capital equipment capacities were ignored because of their external influence to these control loops. However, these considerations might be more dominant in their control of an overall system than the decision loops of this primary/secondary control structure. It is important to each application of this model that the necessary feedback loops and managerial dynamics be included and examined and then adjusted so that the model is more responsive to the goals and objectives of the specific organization.

But the examination of this model was completed to understand the probable response characteristics of this system when implemented within a particular system. The implementation of this system within a series of other upstream and downstream control models would mean many different disturbance frequencies would be transmitted to this control model and the phasing of production and forcasting of production needs would become major concerns along with the ability of this system to maintain acceptable operating levels. If another secondary sector representing capital production capacities was placed in parallel to the labor force secondary, the phasing of expanding the different secondaries would become important to the matching of needed skilled personnel to the available equipment. The flexibilities offered the manager through changing employee productivities and changing his policies regarding system monitoring and system adjustments, would alter the demands for adjustments within the secondary sector. Also in this model it was determined that the secondary sector should be very responsive to the demands of the primary sector. This phenomenon might be similarly desired of the primary sector by other external management control loops that best operate with quick responses from internally nested primary control loops.

The frequency analysis of this system pointed out that the system responses are closely related to the dominant primary control loop or the prime focus of control within the system. It was observed that if previously equal primary adjustment times were changed so that the primary inventory adjustment time (SAFA) was increased and the primary backlog adjustment time (SAMA) was decreased, the system would represent a different conceptualization of system control. The system would no longer be a primary inventory control system that has a backlog control loop to avoid overcorrection within the system. However, the model would represent a production throughput control system with an inventory that acts as a strong buffer between variations in unit production and sales. In this case SAFA would no longer be the dominant control parameter. Instead, the in process backlog adjustment time, SAMA, would be the dominant control parameter.

This level of dominance can be verified by an orthogonal experiment of system parameters. A test was conducted in which SAFA equaled 28 weeks and SAMA, SAAA, and SAAB equaled eight weeks for the standard run while each parameter was orthogonally varied $\pm 25\%$ for the other eight runs. The results of this experiment are summarized in Figure 15 clearly showing the dominance of the primary backlog adjustment time, SAMA, in controlling the primary and secondary damping, secondary excursion, and system finacial measures. Note that the system measures controlled by SAMA and the sign of the influence of SAMA upon these measures is the same as the control that SAFA had in previous experiments. Also note that the sign of the influence SAMA has upon P3DAMP, S2DAMP, S2EXC, and F2 is the opposite sign that SAMA previously had upon those measures, and note that the secondary influences are relatively the same.

The in process backlog control loop is no longer a means to simply adjust attempts to overcorrect the primary inventory, but is itself the dominant control loop of this primary/secondary control system. This emphasizes the necessity to understand for each application of primary/secondary control, what components of a model are meant to be more strongly controlled. Different relationships between primary adjustment times represent different control perspectives for primary/secondary control systems.

To demonstrate the effects of internal flexibilities, two applications of variable model parameters were chosen for the primary/secondary control model. The design region for the standard parameter set was used. The components allowed to vary included the employee productivity, PBAP, and the primary inventory adjustment time, SAFA. The internal system pressures determining the values for these new variables were generated by the combined perceptions of system errors, SAF and SAM, as a percentage of the delayed perception of the production rate, PC. These percentage errors would be negative for inventory and in process shortages and positive for for inventory and in

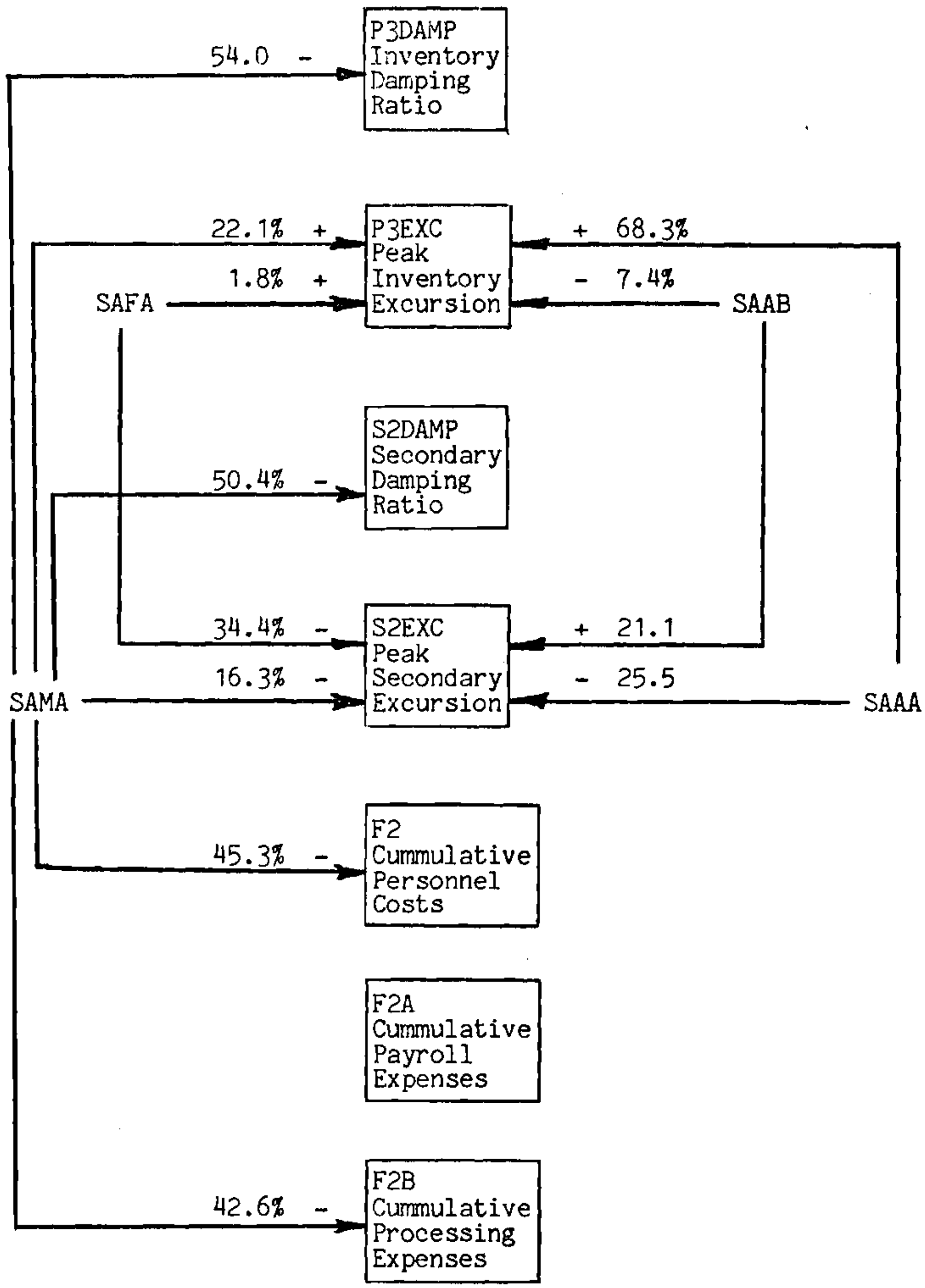

Figure 15. Influence Diagram for Short Backlog Adjustment Time

process surpluses. The employee productivity was allowed to begin varying directly as much as $\pm 25\%$ when these errors amounted to more than two weeks of present production capacity. The production manager's inventory adjustment time decreased by as much as 30% for the same pressure range representing an increased impatience on the part of the manager when in stressful situations. The percentage of adjustments to these variables were determined from plots shown in Figure 16 of the percentage adjustments against the percentage errors.

The use of large error percentages for scaling pressures reflects the acceptability of certain amounts of system error before the institution of these control loops. This might represent a certain degree of patience on the part of the manager or a desire to avoid making a decision in hopes that the problem would simply go away. These implications need further examination.

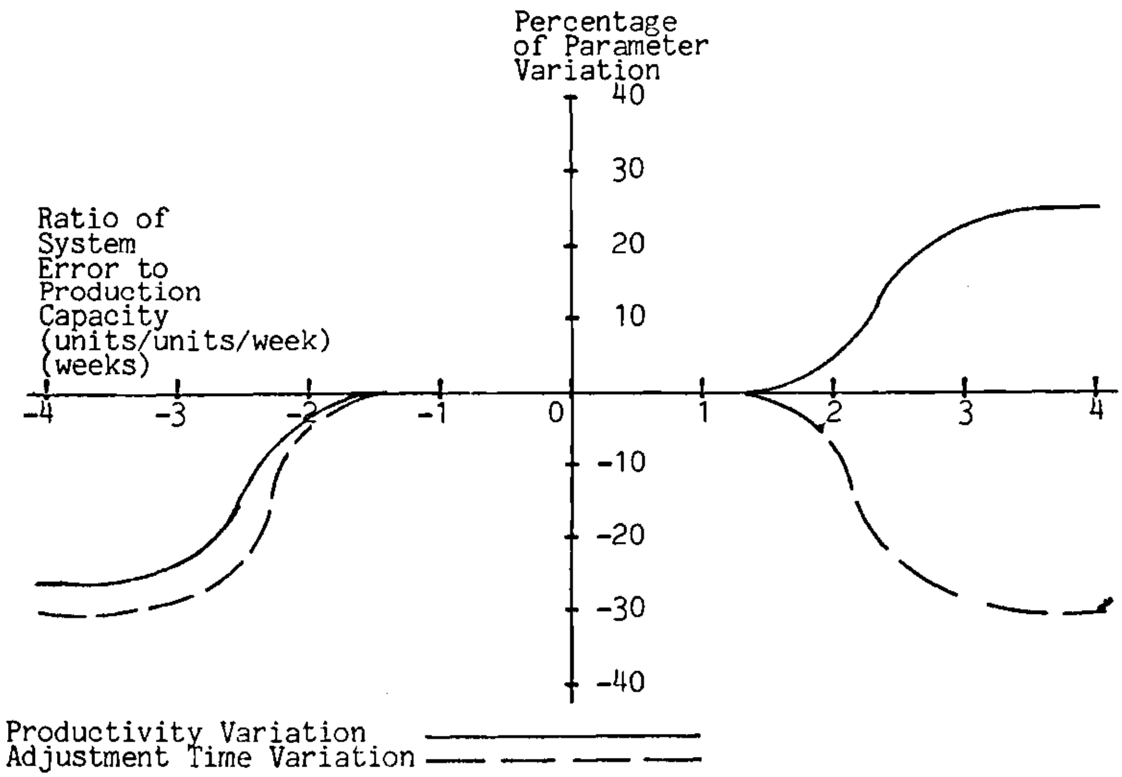

Figure 16. Possible Relationships of Variable Productivity and Variable Adjustment Time to System Errors.

Figure 17 demonstrates the application of these two new internal control loops. Curves labeled 1, 2, and 3 represent the primary inventory level for the standard run, the implemented variable productivity, and the implemented variable adjustment time. Curves labled x, y, and z represent the in process start-up rate for the same runs respectively. A fourth simulation was also made implementing both a variable productivity and adjustment time. System measures supplied by the printed DYNAMO output are summarized in Table 4. Financial measurements were included to demonstrate possible overtime payments to increase employee productivity.

Figure 16 shows that whether there is improvement in the system's response depends on the particular component varied. The flexibility of control added by the variability of the employee productivity causes a distinct improvement to the systems response in decreasing the peak excursions and the system's damping ratio. However, a manager acting more impatiently because of system pressures, increases the load placed on the system. This causes greater excursions in the secondary sector and a less controlled response as measured by the increased damping ratios of the primary and secondary sectors. The fourth simulation incorporating both of these variable components was very nearly equal in its response as compared to the simulation of just the variable productivity. Therefore, at these magnitude levels of component variation, the variable productivity is more influential than the variable inventory adjustment time.

In these simulations with the simple financial measurements utilized, it can be seen that the flexibility of control offered by the variable productivity causes greater costs associated with the labor force while decreasing the necessary costs of employee processing. A particular application of this model might have less costs for processing an employee and greater costs involved in increasing employee productivity. But for this model, decreases in the employee processing costs mean that there are less costs related to nonproductive efforts such as employee orientation and training. Increases in labor costs mean the organization is paying for the opportunity to be more flexible.

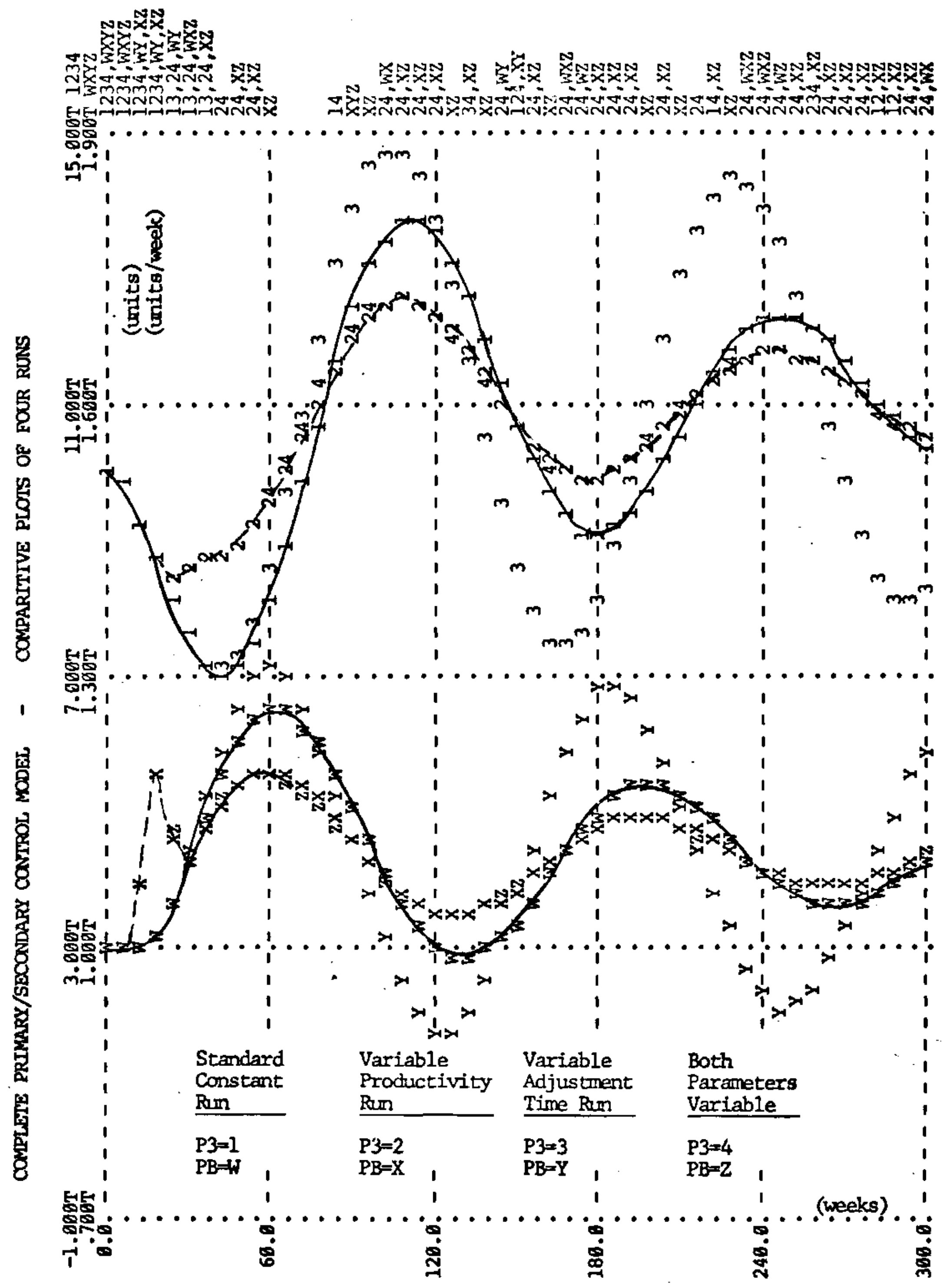

Figure 17. Comparative Plots for Four Combinations of Variability in the Primary Adjustment Time and the Employee Productivity

Table 4. Summary of Sample Simulations

	P3DAMP Inventory Damping Ratio	P3EXC Percentage Inventory Excursion	S2DAMP Workforce Damping Ratio	S2EXC Percentage Workforce Excursion	F2 Cummulative Labor Costs ($1000)	F2A Cummualtive Payroll Costs ($1000)	F2B Cummulative Personnel Processing Costs ($)
Standard Model	0.4821	-29.34%	0.4860	26.33%	14,711	14,141	569,350
Improved Model	0.1181	-28.04%	0.1381	23.69%	14,482	14,165	316,910
Variable Productivity Model	0.4207	-15.34%	0.4850	19.20%	14,544	14,193	350,750
Variable Adjustment Time Model	0.9189	-28.77%	0.9003	31.41%	15,312	14,219	1,093,500
Combined Variable Model	0.4279	-15.34%	0.4850	19.36%	14,551	14,195	356,130

A refinement of these measures is needed in addition to their further analysis for each application of the primary/secondary control system.

Further examination of the other variable components is needed to determine their particular influences. But note that these applications of variable components, like the applications of the standard model structure must be fully investigated with regard to the level of control or responsiveness desired in the specific area of the model application or implementation. Only then can a qualitative value be placed on the desirability of a particular model response.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

The primary/secondary control structure has been described as a common managerial component control model. Secondary control of a primary flow stream exists in many environments. The concept of primary flow stream control by a secondary sector involves the inability of directly changing the inflow to a primary sector without first changing the level of the secondary sector. There are additional information and implementation delays inherent to this control stucture as compared to a direct primary control structure. The secondary sector acts as a momentum device which maintains the system throughput rather than act as a simple delayed information device which only conveys a desired system state. The expanded system delay structure and the existence of a secondary sector as a momentum device causes the primary/secondary control system to be more oscillatory in behavior than a direct primary control system with the same primary management policies.

In a closed loop feedback control system, adjustments to the various states of the system are made incrementally toward desired state levels. While desired state levels may be optimally determined, the implementations of state changes are directed after state errors have been observed and a specific system loading has been determined in order to direct error correction. These functions of state monitoring and adjusting are the delayed functions that help create the dynamic responses of the system. The structural arrangement of these functions and the management policies utilized within these functions determine the responsiveness of the system dynamic.

Because of the self-correcting nature of a management control system, a manager is often faced with many oscillations in the levels of his or her system's inventories, work force, cash flow, productivities, and sales. It is important that the manager not direct adjustments to the system that will only develop into the future problems of the system through increases in the oscillatory tendencies of the control system. Therefore, in determining through model simulation more beneficial management policies, it is important to determine policies that reduce system oscillations. Reductions in system oscillations in model simulations mean that the improved control system is more capable of reducing the errors between the actual system states and the desired system states as determined by the average level of sales. This refers to reductions in the errors between the desired inventory and actual inventory, between the desired production throughput and actual production throughput, between the desired employment level and actual employment level, between the desired productivity and actual productivity, and between the desired cash flow and actual cash flow. These system's errors comprise some of the management focal points of a manager of a production system. But the time relatedness of his decisions about correcting these errors directly affects the long term response of the system that helps generate these system state errors in the future. The results of this study demonstrate that the time related management policies of a primary/secondary control type system internally influence the future errors in system states by increasing or decreasing the oscillatory tendencies that are present in a self-correcting management control system. It is usually easier to change these management policies that determine much of the system loading than it is to change certain system structures or process delay times.

The dominant control loop of the primary sector was determined to be that control loop with the smallest ratio between the primary adjustment time and the total loop delay. For most of the simulations of this primary/secondary control model, the dominant control loop was the primary inventory control loop; and therefore, the primary inventory adjustment time, SAFA, was the dominant control parameter (management policy) of the model. However, the frequency analysis showed the importance of the ratio between the adjustment time and the loop delay and that there are system designs in which the production throughput control loop is the dominant system control loop. In this application of primary/secondary control, the concept of systems control shifts from an inventory control model to a production throughput control model. A patient managerial policy with respect to the primary inventory adjustment time (SAFA) was determined to be desirable to improve the overall system damping characteristics and the excursions of the secondary sector for both cases of primary control. In the inventory control model it is desirable to reduce the in process backlog adjustment time to first increase the system's early transient responsiveness and then avoid the tendency to overcorrect the primary inventory. However, in the production throughput control model, further reductions in the in process adjustment time cause less stability in the control of the system and increase the excursions within the secondary.

While the dominant primary control loop is also the dominant system control loop, the responsiveness of the secondary sector is important in determining much of the overall system's responsiveness. A relatively impatient managerial policy with respect to the secondary accumulation adjustment time, SAAA, will increase the responsiveness of the secondary sector and therefore, reduce the maximum excursion of the primary inventory. The responsiveness of the secondary could also be increased by increasing the secondary process adjustment time (SAAB); however, reducing this term decreases the tendency to overcorrect the secondary sector by reducing the allowable level of employees in process, and thereby reducing the peak excursion of the secondary accumulation. This management policy translates into the reduction of the necessary system's costs of processing the additional employees represented by an increased excursion of the secondary sector. This same secondary excursion and system's cost was also reduced by an increase in the dominant primary adjustment time.

The overall delays in the primary control loops were long enough that high frequency disturbances with periods less than 26 weeks (or time units) would be moderately attenuated. Reductions in information delay times improved the primary damping characteristics and reduced the secondary excursions by increasing the responsiveness of the monitoring systems. However, this reduction might be detrimental in the case of highly responsive primary secondary control systems (not examined) because of the tendency for a reduced information delay to allow high frequency disturbances to be passed through the system.

The results of regional analyses conducted by making large design changes in the length of system delays helped develop general and specific guidelines for the application of primary/secondary control. The lengths of the process and information delays help to determine much of the responsiveness of the various control loops within the system. Shorter delays increase the responsiveness or the natural frequency of the system. The dominant primary adjustment time, either SAFA or SAMA, is predominant in its influence of the control model but must be adjusted accordingly to maintain a proper ratio between itself and the overall delay time within the primary control loop. Extremely short values for the primary process delay time, PCXD, make the influence of the backlog adjustment time, SAMA, very insignificant. Also very long values of the secondary adjustment time, SAAA, remove the oscillatory tendencies of the secondary sector while creating a very unresponsive control situation. The responsiveness of the secondary improves the overall response of the control system by reducing the excursions of the primary inventory and in some cases significantly reducing operating costs and secondary operating characteristics.

The primary/secondary control model is one of a manager's component control models. This system will never appear in this isolated state but will be incorporated inside an organizational control structure including other primary/secondary control models and other component control models. Also the system might include the control loops altering employee productivities, adjustment times, information delay times, and other parameters held constant for most of this systems analysis. The control loops varying these parameters might be more dominant in their influence of the system's responses; however, this thesis demonstrates the importance of the relative magnitudes of these fixed parameters to controlling the responses of the system. Most of all this thesis demonstrates the characteristic responses of a primary/secondary control system so that a manager might better understand the responses of this system when integrated within a total management environment.

The integrated feedback dynamics methodology proved to be a powerful analysis technique of complex feedback systems. Model simulation (time analysis) provided output that enabled comparison of the effects of different parameter adjustments. But when these adjustments were designed into orthogonal experiments, the techniques of statistical regression analysis provided strong measures of the relative effects of different model parameters upon the responses of the system. Finally the frequency analysis of the transformed system of equations 1) enabled a broad examination of large alterations in management policies, 2) demonstrated the primary/secondary control system had a moderate ability to attenuate high frequency disturbances, and 3) showed that the primary/secondary control system had a stong tendency to amplify low frequency disturbances. While the time and statistical analysis techniques may be applied to all modeled systems, the frequency analysis technique is restricted to linear systems or those systems that may be linearized using Taylor series expansions. This condition restricts the use of the complete integrated analysis methodology for complex nonlinear systems. However, it is recommended that components of these complex systems be individually examined where possible according to the techniques of this methodology in order to best understand the possible controlled responses of these system components.

Recommendations for Further Study

This examination of primary/secondary control only begins an understanding of the responses of primary/secondary control models and their responses within larger management control systems. Further investigation should be completed on the effects of different structural arrangements of the system's components. Additional investigation should be carried out on the effects of different control loops varying model parameters such as the system's productivity, information delay times, adjustment times, and process delay times. The system should also be expanded to include certain structural conditions thought to be unnecessary for this early investigation into primary/secondary responses. These additions should include separate attrition, hiring, and firing rates along with separate accumulations for skilled and unskilled employees and accumulations for employees working overtime or layed off. The primary sector should be expanded to keep track of actual backlogged orders and units should be able to be shipped directly from production.

In addition to these internal structural changes, the primary/secondary control system should be examined along with a number of externally structured control systems. The case of parallel secondaries, where both secondaries (e.g. labor force and capital equipment) influence the primary flow stream, should be examined for the importance of phase relationships between the two secondaries in an expanding industry. Also the case of dual control of a primary flow stream by upstream and downstream secondaries (e.g. production force and sales force) should present interesting response dynamics. Finally, the forecasting technique utilized for this analysis is acceptable for a system that would be experiencing only moderate disturbances to the system's sales rate. Desired system states are determined by past sales performance and not projected according to any future expectations. As a result this forecasting technique is not completely satisfactory for systems that are experiencing a growth trend or systems that have predictable market cycles. Additions to the equations for forecasting would be necessary to accomodate these conditions.

APPENDIX

APPENDIX A

EQUATIONS FOR DYNAMO SIMULATION OF SIMPLE PRIMARY/SECONDARY CONTROL MODEL

```
*       INVENTORY CONTROL MODEL - COUPLED PRIMARY/SECONDARY
NOTE
NOTE    PRIMARY SECTOR
NOTE
L     P2.K=P2.J+(DT)*(PB.JK-PC.JK)                  IN PROCESS BACKLOG
L     P2D.K=P2D.J+(DT/P2DD)*(P2.J-P2D.J)            IN PROCESS BACKLOG INFO DELAY
L     P3.K=P3.J+(DT)*(PC.JK-PD.JK)                  PRODUCT INVENTORY
L     P3D.K=P3D.J+(DT/P3DD)*(P3.J-P3D.J)            INVENTORY INFORMATION DELAY
R     PB.KL=(PBAP)*(PBV.K)                          RATE OF PROCESS START UP
L     PBV.K=PBV.J+(DT)*(1/PBVD)*(S2.J-PBV.J)        SMOOTHED LABOR FORCE
R     PC.KL=P2/PCXD                                 PROCESS COMPLETION RATE
R     PD.KL=PDAN+PDN1.K+PDN2.K                      SHIPMENT RATE
A     PDN1.K=STEP(PDNS,PDN1T)                       STEP INPUT
A     PDN2.K=PDN2A*SIN(6.283*TIME.K/PDN2P)          SINE WAVE INPUT
NOTE
NOTE    SECONDARY SECTOR
NOTE
L     S1.K=S1.J+(DT)*(SA.JK-SB.JK)                  TRAINEES,LAYOFFS & OVERTIME
L     S2.K=S2.J+(DT)*(SB.JK)                        LABOR FORCE
R     SA.KL=SAA.K+SAB.K                             LABOR FORCE AUTHORIZATION RATE
A     SAA.K=(SAC.K-S2.K)/SAAA                       AUTHORIZATION PRESSURE
A     SAB.K=-S1.K/SAAB                              BACKLOG ERROR CORRECTION
A     SAC.K=SAD.K/SARP                              DESIRED LABOR FORCE
L     SAD.K=SAD.J+(DT/SADD)*(SAE.J-SAD.J)           SMOOTH DESIRED START RATE
A     SAE.K=SAF.K/SAFA+SAM.K/SAMA+SAH.K             THROUGHPUT & ERROR CORRECTIONS
A     SAF.K=SAG.K-P3D.K                             INVENTORY ERROR
A     SAG.K=(SAH.K)*(SAGA)                          DESIRED INVENTORY
L     SAH.K=SAH.J+(DT/SAHD)*(PD.JK-SAH.J)           AVERAGE SHIPMENT RATE
A     SAM.K=SAN.K-P2D.K                             ERROR IN ORDERS IN PROCESS
A     SAN.K=(SAH.K)*(PCXD)                          DESIRED ORDERS IN PROCESS
R     SB.KL=S1.K/SBXD                               RATE OF CHANGE IN LABOR FORCE
NOTE
NOTE    MODEL CONSTANTS
NOTE
N     P2DD=SAHD     WEEKS                           BACKLOG INFO DELAY TIME
N     P3DD=SAHD     WEEKS                           INVENTORY INFO DELAY TIME
C     PBAP=5        UNITS/PERSON/WEEK               EMPLOYEE NORM PRODUCTIVITY ATT
N     PBVD=SAHD     WKS                             SMOOTH TIME OF LABOR FORCE
C     PCXD=12       WKS                             DESIRED PROCESS DELAY
C     PDAN=1000     UNITS/WK                        STEADY STATE THROUGHPUT
C     PDNS=100      UNITS/WK                        AMPLITUDE OF STEP INPUT
C     PDN1T=5       WKS                             TIME STEP IS IMPLEMENTED
C     PDN2A=0       UNITS/WK                        AMPLITUDE OF SINE WAVE
C     PDN2P=50      WKS                             PERIOD OF SINE WAVE INPUTE
C     SAAA=8        WKS                             SECONDARY ADJUSTMENT TIME
C     SAAB=8        WEEKS                           BACKLOG ADJUSTMENT TIME
N     SADD=SAHD     WEEKS                           PRESSURE SMOOTHING TIME
C     SAFA=20       WKS                             INVENTORY ADJUSTMENT TIME
C     SAGA=10       WKS                             DES TURNOVER TIME OF INVENTORY
C     SAHD=4        WEEKS                           AVG SHIP INFO DELAY TIME
C     SAMA=20       WKS                             ORDERS IN PROCESS ADJUST TIME
C     SARP=5        UNITS/PERSON/WEEK               MANAGERS NORM PRODUCTIVITY ATT
C     SBXD=12       WKS                             TRAINING & AUTHORIZATION DELAY
```

```
NOTE
NOTE       MODEL INITIAL VALUES &/OR EQUATIONS
NOTE
N      P2D=P3XA*PCXD  UNITS                          INITIAL IN PROCESS BACKLOG
N      P2=P3XA*PCXD      UNITS/WEEK                  INITIAL IN PROCESS BACKLOG
N      P3=P3XA*SAGA   UNITS                          INITIAL INVENTORY LEVEL
C      P3XA=1000     UNITS/WEEK                      INITIAL INVENTORY LEVEL
N      P3D=P3        UNITS                           INITIAL INVENTORY LEVEL
N      PBV=S2        PERSONS                         INITIAL SMOOTHED LABOR FORCE
N      S1=0          PERSONS                         INITIAL TRAINEES
N      S2=P3XA/SARP    PERSONS                       INITIAL LABOR FORCE
N      SAD=P3XA      UNITS/WK                        INITIAL PRODUCTION RATE
N      SAH=P3XA      UNITS/WK                        INITIAL PRODUCTION RATE
NOTE
NOTE        OPTIONS AND MODEL SPECIFICATIONS
NOTE
A      DT.K=DTXA+STEP(DTXS,DTXT)                     VARIABLE DT CALCULATION
A      LENGTH.K=LENA                                 LENGTH CHANGE FOR RERUNS
A      PLTPER.K=PLTP+STEP(PLTS,PLTT)                 VARIABLE PLTPER CALCULATION
C      DTXA=.5       WEEK                            CALCULATION INTERVAL
C      DTXS=0        WEEKS                           CALCULATION INTERVAL STEP
C      DTXT=0        WEEKS                           TIME OF STEP IMPLEMENTATION
C      LENA=300      WEEKS                           TIME OF RUN TERMINATION
C      PLTP=6        WEEKS                           INTERVAL OF PLOTTING RESULTS
C      PLTS=0        WEEKS                           PLOTTING INTERVAL STEP
C      PLTT=0        WEEKS                           TIME OF STEP IMPLEMENTATION
SAVE   P3,PB
PLOT   P3=3(-1000,15000)/PB=B(700,1900)
SPEC   SAVPER=6
RUN    INVNT2
```

APPENDIX B

EQUATIONS FOR DYNAMO SIMULATION OF COMPLETE

PRIMARY/SECONDARY CONTROL MODEL

```
*         COMPLETE PRIMARY/SECONDARY CONTROL MODEL
NOTE
NOTE        PRIMARY SECTOR
NOTE
NOTE   P2.K=P2.J+(DT)*(PB.JK-PC.JK)                     IN PROCESS BACKLOG
L      P2D.K=P2D.J+(DT/P2DD)*(P2.J-P2D.J)               IN PROCESS BACKLOG INFO DELAY
L      P3.K=P3.J+(DT)*(PC.JK-PD.JK)                     PRODUCT INVENTORY
L      P3D.K=P3D.J+(DT/P3DD)*(P3.J-P3D.J)               INVENTORY INFORMATION DELAY
R      PB.KL=(PBA.K)*(PBV.K)                            RATE OF PROCESS START UP
L      PBV.K=PBV.J+(DT)*(1/PBVD)*(S2.J-PBV.J)           SMOOTHED LABOR FORCE
R      PC.KL=DELAYP(PB.JK,PCXD,P2.K)                    THIRD ORDER PRODUCTION DELAY
R      PD.KL=PDAN+PDN1.K+PDN2.K                         SHIPMENT RATE
A      PDN1.K=STEP(PDNS,PDN1T)                          STEP INPUT
A      PDN2.K=PDN2A*SIN(6.283*TIME.K/PDN2P)             SINE WAVE INPUT
A      PBA.K=PBB.K*PBAP+PBAP                            VARIABLE PRODUCTIVITY
A      PBB.K=PBC.K*PBBM                                 % PRODUCTIVITY VARIATION
A      PBC.K=TABHL(PBCT,PBD.K,PBCL,PBCH,PBCI)           INCREMENT OF % VARIATION
A      PBD.K=PBF.K/PBE.K                                ERROR AS WEEKS OF PRODUCTION
L      PBE.K=PBE.J+(DT/SAHD)*(PC.JK-PBE.J)              AVERAGE PRODUCTION RATE
A      PBF.K=SAF.K+SAM.K                                TOTAL PRIMARY SECTOR ERRORS
C      PBBM=0                                           SWITCH AND % MULTIPLIER
C      PBCL=-3                                          LOW TABLE VALUE
C      PBCH=3                                           HIGH TABLE VALUE
C      PBCI=1                                           TABLE INCREMENT
T      PBCT=-0.1/0/0/0/0/0/0.1                          PRODUCTIVITY INCREMENTS
NOTE
NOTE        SECONDARY SECTOR
NOTE
L      S1.K=S1.J+(DT)*(SA.JK-SB.JK)                     TRAINEES,LAYOFFS & OVERTIME
L      S2.K=S2.J+(DT)*(SB.JK)                           LABOR FORCE
R      SA.KL=SAA.K+SAB.K                                LABOR FORCE AUTHORIZATION RATE
A      SAA.K=-S1.K/SAAB                                 BACKLOG ERROR CORRECTION
A      SAB.K=(SAC.K-S2.K)/SAAA                          AUTHORIZATION PRESSURE
A      SAC.K=SAD.K/SARP                                 DESIRED LABOR FORCE
L      SAD.K=SAD.J+(DT/SADD)*(SAE.J-SAD.J)              SMOOTH DESIRED START RATE
A      SAE.K=SAF.K/SAFZ.K+SAM.K/SAMA+SAH.K              THROUGHPUT & ERROR CORRECTIONS
A      SAF.K=SAG.K-P3D.K                                INVENTORY ERROR
A      SAG.K=(SAH.K)*(SAGA)                             DESIRED INVENTORY
L      SAH.K=SAH.J+(DT/SAHD)*(PD.JK-SAH.J)              AVERAGE SHIPMENT RATE
A      SAM.K=SAN.K-P2D.K                                ERROR IN ORDERS IN PROCESS
A      SAN.K=(SAH.K)*(PCXD)                             DESIRED ORDERS IN PROCESS
R      SB.KL=S1.K/SBXD                                  RATE OF CHANGE IN LABOR FORCE
A      SAFZ.K=SAFA+SAFA*SAFY.K                          VARIABLE PRIMARY ADJUST TIME
A      SAFY.K=SAFX.K*SAFM                               % ADJUSTMENT TIME VARIATION
A      SAFX.K=TABHL(SAFT,PBD.K,PBCL,PBCH,PBCI)          INCREMENT OF % VARIATION
C      SAFM=0                                           SWITCH AND % MULTIPLIER
T      SAFT=-0.1/0/0/0/0/0/-0.1                         ADJUSTMENT TIME INCREMENTS
NOTE
NOTE        FINANCIAL SECTOR
NOTE
L      F1.K=F1.J+(DT)*(PD.JK-0)                         CUMMULATIVE SALES
N      F1=0.0001      UNITS                             INITIAL SALES
S      F2.K=F2A.K+F2B.K          $                      CUMMULATIVE LABOR COST
L      F2A.K=F2A.J+(DT)*(FA.JK)                         CUMMULATIVE PAYROLL EXPENSES
N      F2A=0        $                                   INITIAL CUMMULATIVE PAYROLL
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```
L      F2B.K=F2B.J+(DT)*(FB.JK)                       CUMMULATIVE HIRE & FIRE EXPENSE
N      F2B=0          $                               INITIAL HIRE & FIRE EXPENSE
L      F3.K=F3.J+(DT)*(PC.JK)                         CUMMULATIVE PRODUCTION
N      F3=0.0001     UNITS                            INITIAL CUMMULATIVE PRODUCTION
R      FA.KL=S2.K*FAXA*(1+PBBM*FAA.K)                 WEEKLY PAYROLL
R      FB.KL=S1.K*FBA.K                               TRAINING & LAYOFF EXPENSES
A      FBA.K=CLIP(FBC.K,FBD.K,S1.K,0)                 DISTINCTION BETWEEN S1 LEVEL
A      FBC.K=FAXA+(FBCA/SBXD)                         TRAINING EXPENSES
A      FBD.K=(-FBDA)                                  SEVERANCE PAY
R      FC.KL=DELAYP(FT.JK,FCXD,F2Q.K)                 LAST QUARTER LABOR COST
R      FT.KL=FA.JK+FB.JK                              WEEKLY LABOR COST
R      FD.KL=DELAYP(PC.JK,FCXD,F3Q.K)                 LAST QUARTER PRODUCTION
S      FSA.K=F1.K*FSAA                                GROSS REVENUES
S      FSB.K=F1.K+P3.K-P3XA                           SALES ADJUSTED BY INVEN CHANGE
S      FSC.K=F2.K/F3.K       $/UNIT                   RUNNING COST/UNIT
S      FSD.K=F2Q.K/F3Q.K                              QUARTERLY LABOR COST/UNIT
C      FAXA=200        $/MAN/WEEK                     WEEKLY PAY SCALE
C      FBCA=1000       $/PERSON                       INITIAL TRAINING COST
C      FBDA=200        $/MAN/WEEK                     SEVERANCE PAY
C      FCXD=12         WEEKS                          LENGTH OF QUARTER
C      FSAA=200        $/UNIT                         UNIT PRICE
A      FAA.K=TABHL(FAAT,PBD,PBCL,PBCH,PBCI)           INCREMENT OF OVERTIME
T      FAAT=0/0/0/0/0/0/.15                           OVERTIME INCREMENTS
NOTE
NOTE     MODEL CONSTANTS
NOTE
N      P2DD=SAHD     WEEKS                            BACKLOG INFO DELAY TIME
N      P3DD=SAHD     WEEKS                            INVENTORY INFO DELAY TIME
C      PBAP=5        UNITS/PERSON/WEEK                EMPLOYEE NORM PRODUCTIVITY ATT
N      PBVD=SAHD     WKS                              SMOOTH TIME OF LABOR FORCE
C      PCXD=12       WKS                              DESIRED PROCESS DELAY
C      PDAN=1000     UNITS/WK                         STEADY STATE THROUGHPUT
C      PDNS=100      UNITS/WK                         AMPLITUDE OF STEP INPUT
C      PDN1T=5       WKS.                             TIME STEP IS IMPLEMENTED
C      PDN2A=0       UNITS/WK                         AMPLITUDE OF SINE WAVE
C      PDN2P=50      WKS                              PERIOD OF SINE WAVE INPUTE
C      SAAA=8        WKS                              SECONDARY ADJUSTMENT TIME
C      SAAB=8        WEEKS                            BACKLOG ADJUSTMENT TIME
N      SADD=SAHD     WEEKS                            PRESSURE SMOOTHING TIME
C      SAFA=20       WKS                              INVENTORY ADJUSTMENT TIME
C      SAGA=10       WKS                              DES TURNOVER TIME OF INVENTORY
C      SAHD=4        WEEKS                            AVG SHIP INFO DELAY TIME
C      SAMA=20       WKS                              ORDERS IN PROCESS ADJUST TIME
C      SARP=5        UNITS/PERSON/WEEK                MANAGERS NORM PRODUCTIVITY ATT
C      SBXD=12       WKS                              TRAINING & AUTHORIZATION DELAY
NOTE
NOTE     MODEL INITIAL VALUES &/OR EQUATIONS
NOTE
N      P2D=PB*PCXD   UNITS                            INITIAL IN PROCESS BACKLOG
N      PB=P3XA       UNITS/WEEK                       FOR INITIAL IN PROCESS BACKLOG
N      P3=P3XA*SAGA    UNITS                          INITIAL INVENTORY LEVEL
C      P3XA=1000     UNITS/WEEK                       INITIAL INVENTORY LEVEL
N      P3D=P3        UNITS                            INITIAL INVENTORY LEVEL
N      PBE=P3XA                                       INITIAL VALUE PROD RATE
N      PBV=S2        PERSONS                          INITIAL SMOOTHED LABOR FORCE
N      S1=0          PERSONS                          INITIAL TRAINEES
N      S2=P3XA/SARP    PERSONS                        INITIAL LABOR FORCE
N      SAD=P3XA      UNITS/WK                         INITIAL PRODUCTION RATE
N      SAH=P3XA      UNITS/WK                         INITIAL PRODUCTION RATE
NOTE
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NOTE      MACRO EQUATIONS FOR DAMPING CHARACTERISTICS AND
NOTE          PERCENTAGE EXCURSION VALUES
NOTE
NOTE        THE DAMPING CHARACTERISTIC IS CALCULATED FOR "VAR"
NOTE        "STAND" IS THE MEAN VALUE OF THE VARIABLE USED HERE AS STANDARD
NOTE        THE MACRO IS TURNED ON AT VARIABLE STEP TIME "VST"
NOTE        EQUATIONS ARE FOR DAMPING CHARACTERISTICS OF COSINE TYPE OSCILATIONS
NOTE          FOR SINE TYPE OSCILATIONS USE (-VAR) IN PLACE OF "VAR.K"
NOTE          AND(-STAND) IN PLACE OF "STAND" IN MACRO COMMAND.
NOTE
MACRO DAMPR(VAR,STAND,VST,EXC,STANDI)                  MACRO FORMAT
L      $V.K=$V.J+(DT)*($DM)*(VAR.J-$V.J)               OSCILATING VARIABLE USED IN MAC
N      $DM=1/DT                                        CORRECTS  FOR DT CHANGE (STORAG
N      $V=VAR
L      $VS.K=$VS.J+(DT)*($DM)*($VA.J-$VS.J)            DELAYED OSCILATING VARIABLE
N      $VS=$V
A      $VA.K=$V.K                                      AUXILARY FORCING DELAY IN $V
A      $VD.K=STEP($VS.K,VST)                           MACRO SWITCHED ON AT VST
A      $A.K=CLIP($VD.K,$AX.K,$V.K,$VD.K)               MIN/MAX SEARCH
A      $AX.K=SWITCH(0,$VD.K,$D.K)                      SETS AND HOLDS INITIAL VALUES
L      $B.K=$B.J+(DT)*($DM)*($A.J-$B.J)                DELAYED VALUE OF $A.K
N      $B=0
A      $C.K=SWITCH($A.K,$D.K,$B.K)                     SWITCH OF THE INPUT TO $D.K
L      $D.K=$D.J+(DT)*($DM)*($C.J-$D.J)                FIRST MIN MAX
N      $D=0
A      $E.K=SWITCH(0,$F.K,$B.K)                        SETS AND HOLDS INITIAL VALUES
A      $F.K=CLIP($FX.K,$G.K,$V.K,$VD.K)                MIN/MAX SEARCH
A      $FX.K=SWITCH(0,$G.K,$FQ.K)                      SETS AND HOLDS INITIAL VALUES
L      $FQ.K=$FQ.J+(DT)*($DM)*($FR.J)                  COUNTING SWITCH (COUNTS 1/2 PER
N      $FQ=0
A      $FR.K=SWITCH(0,$FS.K,$B.K)                      SWITCH TO SECOND OSCILATION CAL
A      $FS.K=SWITCH(1,0,$G.K)                          TURNS ON COUNTER(COUNTS 1/2 PER
A      $G.K=CLIP($VD.K,$GX.K,$V.K,$VD.K)               MIN/MAX SEARCH
A      $GX.K=SWITCH(0,$VD.K,$K.K)                      SETS AND HOLDS INITIAL VALUES
L      $H.K=$H.J+(DT)*($DM)*($E.J-$H.J)                DELAYED VALUE OF $E.K
N      $H=0
A      $J.K=SWITCH($E.K,$K.K,$H.K)                     SWITCH OF THE INPUT TO $K.K
L      $K.K=$K.J+(DT)*($DM)*($J.J-$K.J)                SECOND MIN/MAX
N      $K=0
A      DAMPR.K=(STAND-$K.K)/(STAND-$D.K)               DAMPING CHARACTERISTICS OF VAR
A      EXC.K=($D.K-STANDI)/STANDI                      MAGNITUDE PERCENTAGE EXCURSION
MEND
A      P3DAMP.K=DAMPR(P3.K,P3STD,P3VST,P3EXC,P3STI) DAMPING CHARACTERISTICS OF P3
C      P3STI=10000  UNITS.                             INITIAL VALUE OF P3
C      P3STD=11000  UNITS                              MEAN VALUE OF P3 OSCILATION
C      P3VST=10      WKS                               MACRO SWITCHED ON
A      S2DAMP.K=DAMPR(-S2.K,-S2STD,S2VST,S2EXC,-S2STI)       DAMPING CHARAC OF S2
C      S2STI=200
C      S2STD=220     PERSONS                           MEAN VALUE OF OSCLLATION
C      S2VST=25      WKS                               MACRO SWITCHED ON
NOTE
NOTE        OPTIONS AND MODEL SPECIFICATIONS
NOTE
OPT    PCL=14
OPT    D
OPT    MSP=60
NOTE
A      DT.K=DTXA+STEP(DTXS,DTXT)                       VARIABLE DT CALCULATION
A      LENGTH.K=LENA                                   LENGTH CHANGE FOR RERUNS
A      PRTPER.K=PRTP+STEP(PRTS,PRTT)                   VARIABLE PRTPER CALCULATION
A      PLTPER.K=PLTP+STEP(PLTS,PLTT)                   VARIABLE PLTPER CALCULATION
C      DTXA=.5       WEEK                              CALCULATION INTERVAL
C      DTXS=0        WEEKS                             CALCULATION INTERVAL STEP
C      DTXT=0        WEEKS                             TIME OF STEP IMPLEMENTATION
```

```
C      LENA=300      WEEKS                          TIME OF RUN TERMINATION
C      PRTP=300      WEEKS                          INTERVAL OF RESULT TABULATION
C      PRTS=0        WEEKS                          TABULATION INTERVAL STEP
C      PRTT=0        WEEKS                          TIME OF STEP IMPLEMENTATION
C      PLTP=6      WEEKS                            INTERVAL OF PLOTTING RESULTS
C      PLTS=0        WEEKS                          PLOTTING INTERVAL STEP
C      PLTT=0        WEEKS                          TIME OF STEP IMPLEMENTATION
SAVE   P3,PB
PRINT  P3,P3DAMP,P3EXC,S1,S2,S2DAMP,S2EXC,SA,F2,F2A,F2B
PLOT   P3=3(-1000,15000)/PB=B(700,1900)
SPEC   SAVPER=6
RUN    INVENT
```

APPENDIX C

SIMULATION RESULTS FROM ORTHOGONAL TESTS OF THE PRIMARY/SECONDARY CONTROL MODEL

DESIGN REGION 1A

25% VARIATION IN SAAA, SAFA, SAMA, SAAB

RUN	SAAA	SAFA	SAMA	SAAB	D13	D23	D123	P3DAMP	P3EXC	S2DAMP	S2EXC	F2	F2A	F2B
0	2.0	14.0	14.0	2.0	0	0	0	.2104	-12.50	.2100	24.32	13367	13244	122800
1	1.5	10.5	10.5	2.5	1	1	-1	.3705	-11.14	.3704	27.79	13435	13245	189620
2	2.5	10.5	10.5	1.5	-1	1	1	.6078	-12.82	.6067	28.39	13516	13235	281300
3	1.5	17.5	10.5	1.5	1	-1	1	.0542	-12.37	.0546	21.54	13326	13244	82221
4	2.5	17.5	10.5	2.5	-1	-1	-1	.0755	-13.14	.0758	21.93	13331	13244	87277
5	1.5	10.5	17.5	2.5	-1	-1	1	.4456	-11.24	.4446	27.91	13461	13245	215980
6	2.5	10.5	17.5	1.5	1	-1	-1	.7028	-12.94	.7003	28.58	13565	13240	325030
7	1.5	17.5	17.5	1.5	-1	1	-1	.0829	-12.53	.0828	21.62	13331	13244	86709
8	2.5	17.5	17.5	2.5	1	1	1	.1093	-13.31	.1091	22.01	13336	13244	92501

DESIGN REGION 1B

25% VARIATION IN SAAA, SAFA, SAMA, SAAB

RUN	SAAA	SAFA	SAMA	SAAB	D13	D23	D123	P3DAMP	P3EXC	S2DAMP	S2EXC	F2	F2A	F2B
0	8	14.0	14.0	8	0	0	0	.4734	-15.81	.4726	25.17	13417	13233	184100
1	6	10.5	10.5	10	1	1	-1	.7749	-13.93	.7720	29.43	13635	13258	377600
2	10	10.5	10.5	6	-1	1	1	1.0286	-16.11	1.0277	28.51	13583	13129	453780
3	6	17.5	10.5	6	1	-1	1	.1596	-15.24	.1599	22.47	13346	13244	102460
4	10	17.5	10.5	10	-1	-1	-1	.2460	-17.07	.2463	22.43	13361	13247	114430
5	6	10.5	17.5	10	-1	-1	1	.8818	-14.06	.8775	29.62	13738	13294	444400
6	10	10.5	17.5	6	1	-1	-1	1.1501	-16.27	1.1482	28.79	13584	13082	501910
7	6	17.5	17.5	6	-1	1	-1	.2079	-15.44	.2075	22.61	13354	13243	110270
8	10	17.5	17.5	10	1	1	1	.3054	-17.29	.3051	22.64	13374	13250	124640

DESIGN REGION 2A

25% VARIATION IN SAAA, SAFA, SAMA, SAAB

RUN	SAAA	SAFA	SAMA	SAAB	D13	D23	D123	P3DAMP	P3EXC	S2DAMP	S2EXC	F2	F2A	F2B
0	2.0	20	20	2.0	0	0	0	.1760	-16.96	.1760	20.59	13337	13245	92613
1	1.5	15	15	2.5	1	1	-1	.3049	-15.10	.3051	22.63	13369	13244	125020
2	2.5	15	15	1.5	-1	1	1	.4813	-17.28	.4812	23.89	13426	13260	166040
3	1.5	25	15	1.5	1	-1	1	.0578	-16.97	.0580	18.52	13312	13244	68306
4	2.5	25	15	2.5	-1	-1	-1	.0722	-17.83	.0720	18.87	13315	13243	71541
5	1.5	15	25	2.5	-1	-1	1	.3517	-15.23	.3517	22.83	13379	13245	133920
6	2.5	15	25	1.5	1	-1	-1	.5405	-17.44	.5400	24.09	13446	13267	179030
7	1.5	25	25	1.5	-1	1	-1	.0773	-17.18	.0770	18.68	13315	13243	71121
8	2.5	25	25	2.5	1	1	1	.0943	-18.05	.0940	19.03	13318	13243	74613

DESIGN REGION 2B

25% VARIATION IN SAAA, SAFA, SAMA, SAAB

RUN	SAAA	SAFA	SAMA	SAAB	D13	D23	D123	P3DAMP	P3EXC	S2DAMP	S2EXC	F2	F2A	F2B
0	8	20	20	8	0	0	0	.3763	-21.04	.3763	22.20	13355	13227	127700
1	6	15	15	10	1	1	-1	.5853	-18.49	.5847	24.71	13469	13275	194370
2	10	15	15	6	-1	1	1	.8732	-21.45	.8737	25.42	13445	13188	256880
3	6	25	15	6	1	-1	1	.1328	-20.39	.1330	19.77	13324	13242	82185
4	10	25	15	10	-1	-1	-1	.2073	-22.73	.2080	20.31	13334	13243	90979
5	6	15	25	10	-1	-1	1	.6512	-18.65	.6502	24.90	13493	13283	209680
6	10	15	25	6	1	-1	-1	.9523	-21.63	.9523	25.63	13434	13161	273460
7	6	25	25	6	-1	1	-1	.1635	-20.63	.1630	19.93	13327	13241	85862
8	10	25	25	10	1	1	1	.2455	-23.00	.2460	20.49	13340	13245	95006

DESIGN REGION 3A

25% VARIATION IN SAAA, SAFA, SAMA, SAAB

RUN	SAAA	SAFA	SAMA	SAAB	D13	D23	D123	P3DAMP	P3EXC	S2DAMP	S2EXC	F2	F2A	F2B
0	2.0	20	20	2.0	0	0	0	.1809	-23.68	.1845	24.08	13401	13285	115330
1	1.5	15	15	2.5	1	1	-1	.3152	-21.55	.3246	27.16	13447	13282	164360
2	2.5	15	15	1.5	-1	1	1	.4954	-23.74	.5061	28.36	13522	13304	217310
3	1.5	25	15	1.5	1	-1	1	.0309	-23.13	.0407	21.88	13364	13284	79931
4	2.5	25	15	2.5	-1	-1	-1	.0404	-23.97	.0523	22.27	13368	13284	83833
5	1.5	15	25	2.5	-1	-1	1	.5606	-22.29	.5589	27.35	13535	13317	218050
6	2.5	15	25	1.5	1	-1	-1	.7916	-24.52	.7882	28.61	13616	13328	288280
7	1.5	25	25	1.5	-1	1	-1	.0790	-24.12	.0803	21.52	13369	13283	85689
8	2.5	25	25	2.5	1	1	1	.0964	-24.99	.0979	21.89	13373	13283	89920

DESIGN REGION 3B

25% VARIATION IN SAAA, SAFA, SAMA, SAAB

RUN	SAAA	SAFA	SAMA	SAAB	D13	D23	D123	P3DAMP	P3EXC	S2DAMP	S2EXC	F2	F2A	F2B
0	8	20	20	8	0	0	0	.3846	-27.73	.3891	25.56	13422	13263	158490
1	6	15	15	10	1	1	-1	.6024	-24.94	.6130	29.24	13582	13327	254400
2	10	15	15	6	-1	1	1	.8919	-27.88	.9030	29.52	13558	13229	329790
3	6	25	15	6	1	-1	1	.0818	-26.45	.0987	23.05	13380	13284	95437
4	10	25	15	10	-1	-1	-1	.1315	-28.68	.1496	23.26	13386	13282	104470
5	6	15	25	10	-1	-1	1	.9237	-25.74	.9189	29.44	13639	13302	337240
6	10	15	25	6	1	-1	-1	1.2853	-28.79	1.2815	30.04	13388	13014	373510
7	6	25	25	6	-1	1	-1	.1669	-27.54	.1688	22.75	13383	13280	103270
8	10	25	25	10	1	1	1	.2497	-29.87	.2519	23.18	13396	13283	113160

DESIGN REGION 4A

25% VARIATION IN SAAA, SAFA, SAMA, SAAB

RUN	SAAA	SAFA	SAMA	SAAB	D13	D23	D123	P3DAMP	P3EXC	S2DAMP	S2EXC	F2	F2A	F2B
0	8	28	28	8	0	0	0	.3655	-29.12	.3651	21.21	13598	13278	320010
1	6	21	21	10	1	1	-1	.5720	-24.98	.5685	24.10	13704	13205	499070
2	10	21	21	6	-1	1	1	.8356	-30.94	.8359	23.44	13809	13344	465020
3	6	35	21	6	1	-1	1	.1394	-28.47	.1390	18.98	13471	13248	222150
4	10	35	21	10	-1	-1	-1	.1996	-31.20	.2000	19.57	13485	13243	242410
5	6	21	35	10	-1	-1	1	.6193	-25.15	.6156	24.21	13719	13203	515530
6	10	21	35	6	1	-1	-1	.8903	-31.17	.8904	23.60	13824	13347	477050
7	6	35	35	6	-1	1	-1	.1619	-28.74	.1620	19.10	13477	13248	228470
8	10	35	35	10	1	1	1	.2267	-31.49	.2270	19.69	13490	13240	249400

DESIGN REGION 4B

25% VARIATION IN SAAA, SAFA, SAMA, SAAB

RUN	SAAA	SAFA	SAMA	SAAB	D13	D23	D123	P3DAMP	P3EXC	S2DAMP	S2EXC	F2	F2A	F2B
0	16	28	28	16	0	0	0	.5533	-33.67	.5529	22.08	16351	15950	401020
1	12	21	21	20	1	1	-1	.9040	-28.88	.9004	25.43	16525	15764	761670
2	20	21	21	12	-1	1	1	1.0780	-35.39	1.0781	24.15	16672	16088	583690
3	12	35	21	12	1	-1	1	.2294	-32.42	.2290	19.77	16165	15902	263030
4	20	35	21	20	-1	-1	-1	.3362	-36.64	.3360	20.27	16188	15904	284640
5	12	21	35	20	-1	-1	1	.9627	-29.07	.9587	25.56	16528	15741	787600
6	20	21	35	12	1	-1	-1	1.1392	-35.64	1.1391	24.33	16706	16107	598640
7	12	35	35	12	-1	1	-1	.2584	-32.71	.2580	19.90	16178	15907	271510
8	20	35	35	20	1	1	1	.3711	-36.97	.3710	20.41	16196	15903	292830

DESIGN REGION 5A

25% VARIATION IN SAAA, SAMA, SAAB, PCXD, SBXD, SAHD

RUN	SAAA	D14	SAMA	SAAB	PCXD	SBXD	SAHD	P3DAMP	P3EXC	S2DAMP	S2EXC	F2	F2A	F2B
0	8	0	20	8	12	12	4	.4821	-29.34	.4863	26.33	13793	13245	548080
1	6	-1	15	10	15	15	3	.2977	-26.81	.3607	28.89	13990	13288	701630
2	10	-1	15	6	9	15	5	.5995	-33.38	.6017	24.35	13923	13358	565220
3	6	1	15	6	15	9	5	.3708	-29.78	.4131	28.73	13794	13315	479410
4	10	1	15	10	9	9	3	.2395	-24.40	.2473	24.13	13574	13270	304330
5	6	-1	25	10	9	9	5	.5027	-26.36	.4980	27.10	13754	13272	481790
6	10	-1	25	6	15	9	3	.4386	-30.09	.4394	24.76	13644	13285	359380
7	6	1	25	6	9	15	3	.3973	-25.56	.3973	23.81	13765	13245	520220
8	10	1	25	10	15	15	5	.9501	-36.18	.9489	28.65	14343	13420	922410

DESIGN REGION 5A

25% VARIATION IN SAAA, SAMA, SAAB

RUN	SAAA	D14	SAMA	SAAB	D13	D23	D123	P3DAMP	P3EXC	S2DAMP	S2EXC	F2	F2A	F2B
0	8	0	12	8	0	0	0	.1676	-28.52	.2111	24.66	13659	13287	37156
1	6	-1	9	10	1	1	-1	.3897	-25.54	.5688	28.59	14131	13302	82850
2	10	-1	9	6	-1	1	1	.1246	-30.01	.1623	22.72	13587	13284	30350
3	6	1	9	6	1	-1	1	.2327	-26.52	.3240	25.53	13740	13280	45989
4	10	1	9	10	-1	-1	-1	.2511	-28.64	.3447	25.46	13753	13286	46712
5	6	-1	15	10	-1	-1	1	.1761	-26.83	.2194	26.31	13698	13284	41462
6	10	-1	15	6	1	-1	-1	.1930	-31.78	.2000	22.40	13601	13291	31005
7	6	1	15	6	-1	1	-1	.1418	-27.95	.1618	24.10	13620	13284	33587
8	10	1	15	10	1	1	1	.2118	-30.20	.2322	24.37	13650	13276	37434

DESIGN REGION 5A

25% VARIATION IN SAAA, SAFA, SAMA, SAAB

RUN	SAAA	SAFA	SAMA	SAAB	D13	D23	D123	P3DAMP	P3EXC	S2DAMP	S2EXC	F2	F2A	F2B
0	8	28	8	8	0	0	0	.3039	-27.46	.4098	24.84	13773	13278	49422
1	6	21	6	10	1	1	-1	.8363	-24.20	1.3077	33.13	14500	13200	140000
2	10	21	6	6	-1	1	1	.2996	-28.17	.4155	25.12	13782	13281	50138
3	6	35	6	6	1	-1	1	.5750	-25.55	.7523	25.58	14201	13281	92032
4	10	35	6	10	-1	-1	-1	.5466	-27.59	.7229	25.06	14100	13295	80462
5	6	21	10	10	-1	-1	1	.3649	-25.63	.5071	29.38	14060	13289	77135
6	10	21	10	6	1	-1	-1	.1955	-30.10	.2246	23.82	13635	13277	35847
7	6	35	10	6	-1	1	-1	.2251	-27.39	.2432	22.22	13589	13283	30642
8	10	35	10	10	1	1	1	.1974	-29.62	.2310	22.10	13586	13284	30262

DESIGN REGION 6A

25% VARIATION IN SAAA, SAFA, SAMA, SAAB

RUN	SAAA	SAFA	SAMA	SAAB	D13	D23	D123	P3DAMP	P3EXC	S2DAMP	S2EXC	F2	F2A	F2B
0	8	28	28	8	0	0	0	.3704	-35.98	.3715	23.56	13704	13327	377280
1	6	21	21	10	1	1	-1	.5849	-31.66	.5859	27.54	13848	13228	620040
2	10	21	21	6	-1	1	1	.8451	-37.42	.8478	25.98	13967	13417	550730
3	6	35	21	6	1	-1	1	.0794	-34.58	.0857	21.01	13532	13288	244320
4	10	35	21	10	-1	-1	-1	.1251	-37.18	.1323	21.49	13558	13293	265790
5	6	21	35	10	-1	-1	1	.8219	-32.52	.8143	27.65	13960	13272	687770
6	10	21	35	6	1	-1	-1	1.1467	-38.54	1.1455	26.64	14014	13406	608440
7	6	35	35	6	-1	1	-1	.1638	-35.84	.1644	21.06	13556	13291	264370
8	10	35	35	10	1	1	1	.2291	-38.52	.2296	21.60	13570	13283	286440

DESIGN REGION 6B

25% VARIATION IN SAAA, SAFA, SAMA, SAAB

RUN	SAAA	SAFA	SAMA	SAAB	D13	D23	D123	P3DAMP	P3EXC	S2DAMP	S2EXC	F2	F2A	F2B
0	16	28	28	16	0	0	0	.5590	-40.40	.5601	24.26	16464	15998	466830
1	12	21	21	20	1	1	-1	.9189	-35.48	.9206	28.68	16718	15782	936230
2	20	21	21	12	-1	1	1	1.0882	-41.71	1.0900	26.48	16845	16161	683930
3	12	35	21	12	1	-1	1	.1478	-38.33	.1551	21.63	16208	15928	280120
4	20	35	21	20	-1	-1	-1	.2294	-42.27	.2358	21.82	16252	15948	303700
5	12	21	35	20	-1	-1	1	1.2116	-36.45	1.2023	28.97	16678	15676	1002100
6	20	21	35	12	1	-1	-1	1.4277	-42.95	1.4264	27.22	17022	16272	749730
7	12	35	35	12	-1	1	-1	.2610	-39.71	.2614	21.78	16263	15951	312260
8	20	35	35	20	1	1	1	.3739	-43.82	.3745	22.15	16285	15952	332590

APPENDIX D

STATISTICAL INFLUENCE DATA

SIGNIFYING MAGNITUDE AND POLARITY OF INFLUENCE

DESIGN REGION 1B

25% VARIATION IN SAAA,SAFA,SAMA,SAAB

PARAMETERS	P3DAMP	P2EXC	S2DAMP	S2EXC	F2	F2A	F2B
SAFA	-91.0	+24.8	-90.9	-98.6	-87.4	+16.4	+93.2
SAAA	+ 5.3	+73.9	+ 5.4	n.s.	n.s.	-36.9	n.s.
SAAB	n.s.	n.s.	n.s.	n.s.	n.s.	+41.5	n.s.
SAMA	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

DESIGN REGION 2A

25% VARIATION IN SAAA,SAFA,SAMA,SAAB

PARAMETERS	P3DAMP	P2EXC	S2DAMP	S2EXC	F2	F2A	F2B
SAFA	-85.1	+35.5	-85.2	-95.5	-78.0	-36.7	-84.7
SAAA	+ 7.1	+53.6	+ 7.0	n.s.	+10.2	+27.2	+ 7.2
SAAB	- 5.0	-10.1	- 5.0	n.s.	- 8.4	-30.2	- 5.3
SAMA	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

DESIGN REGION 2B

25% VARIATION IN SAAA,SAFA,SAMA,SAAB

PARAMETERS	P3DAMP	P2EXC	S2DAMP	S2EXC	F2	F2A	F2B
SAFA	-86.1	+26.9	-86.0	-97.9	-90.0	+ 4.3	-88.8
SAAA	+ 8.9	+71.5	+ 9.0	n.s.	n.s.	-43.7	+ 5.5
SAAB	n.s.	n.s.	n.s.	n.s.	n.s.	+48.1	n.s.
SAMA	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

* n.s. - not significant statistically

DESIGN REGION 3A

25% VARIATION IN SAAA,SAFA,SAMA,SAAB

PARAMETERS	P3DAMP	P2EXC	S2DAMP	S2EXC	F2	F2A	F2B
SAFA	-77.7	+22.6	-78.5	-96.7	-76.0	-48.0	-80.5
SAAA	n.s.	+50.3	n.s.	n.s.	n.s.	n.s.	n.s.
SAMA	+ 8.8	+16.7	n.s.	n.s.	n.s.	+16.6	n.s.
SAMA	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

DESIGN REGION 3B

25% VARIATION IN SAAA,SAFA,SAMA,SAAB

PARAMETERS	P3DAMP	P2EXC	S2DAMP	S2EXC	F2	F2A	F2B
SAFA	-81.3	+17.2	-81.7	-98.8	-56.9	n.s.	-90.3
SAAA	n.s.	+70.9	n.s.	n.s.	n.s.	n.s.	n.s.
SAMA	n.s.	+10.1	n.s.	n.s.	n.s.	n.s.	n.s.
SAMA	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

DESIGN REGION 4A

25% VARIATION IN SAAA,SAFA,SAMA,SAAB

PARAMETERS	P3DAMP	P2EXC	S2DAMP	S2EXC	F2	F2A	F2B
SAFA	-87.5	+14.4	-87.1	-97.8	-93.0	- 8.0	-97.3
SAAA	+ 7.9	+74.9	+ 8.2	n.s.	n.s.	+41.1	n.s.
SAAB	n.s.	-10.4	n.s.	n.s.	n.s.	-49.4	n.s.
SAMA	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

DESIGN REGION 4B

25% VARIATION IN SAAA,SAFA,SAMA,SAAB

PARAMETERS	P3DAMP	P2EXC	S2DAMP	S2EXC	F2	F2A	F2B
SAFA	-94.8	+16.3	-94.7	-95.8	-92.5	n.s.	-89.1
SAAA	+ 3.7	+79.8	+ 3.8	n.s.	+ 4.3	+48.7	- 3.6
SAAB	n.s.	n.s.	n.s.	+ 3.2	- 2.6	-49.3	+ 5.7
SAMA	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

DESIGN REGION 5A

25% VARIATION IN SAAA,SAFA,SAMA,SAAB,SAHD,PCXD,SBXD

PARAMETERS	P3DAMP	P2EXC	S2DAMP	S2EXC	F2	F2A	F2B
SAFA	-82.8	n.s.	-84.0	-71.8	-64.4	n.s.	-75.3
SAHD	+ 9.4	+36.1	+ 9.7	+ 4.2	n.s.	+54.7	n.s.
SAAA	n.s.	+23.4	n.s.	- 6.6	n.s.	n.s.	n.s.
SAAB	n.s.	n.s.	n.s.	+ 6.1	n.s.	n.s.	n.s.
PCXD	n.s.	+19.5	n.s.	+10.7	n.s.	n.s.	n.s.
SBXD	n.s.	+14.4	n.s.	n.s.	n.s.	n.s.	n.s.
SAMA	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

DESIGN REGION 5A

25% VARIATION IN SAAA,SAMA,SAAB,SAHD,PCXD,SBXD

PARAMETERS	P3DAMP	P2EXC	S2DAMP	S2EXC	F2	F2A	F2B
SAHD	+39.7	+37.8	+40.9	+18.3	+21.6	n.s.	+14.8
SBXD	+17.3	+13.6	+20.0	n.s.	+48.2	n.s.	+54.7
PCXD	n.s.	+18.4	+20.0	+47.2	+17.4	n.s.	+16.3
SAAA	+15.6	+25.7	+12.8	-15.4	n.s.	n.s.	n.s.
SAAB	n.s.	n.s.	n.s.	+17.7	+ 8.8	n.s.	+11.0
SAMA	+22.0	n.s.	+17.3	n.s.	n.s.	n.s.	n.s.

DESIGN REGION 5A

25% VARIATION IN SAAA,SAMA,SAAB

PARAMETERS	P3DAMP	P2EXC	S2DAMP	S2EXC	F2	F2A	F2B
SAAA	+25.1	+81.2	+26.1	-36.4	n.s.	n.s.	- 6.9
SAAB	n.s.	-11.1	n.s.	+60.5	+31.4	n.s.	+59.2
SAMA	+71.4	+ 7.0	+67.5	n.s.	+33.3	n.s.	+30.2

DESIGN REGION 5A

25% VARIATION IN SAAA,SAFA,SAMA,SAAB

PARAMETERS	P3DAMP	P2EXC	S2DAMP	S2EXC	F2	F2A	F2B
SAFA	n.s.	+ 1.8	n.s.	-34.4	n.s.	n.s.	n.s.
SAAA	n.s.	+68.3	n.s.	-25.5	n.s.	n.s.	n.s.
SAAB	n.s.	- 7.4	n.s.	+21.1	n.s.	n.s.	n.s.
SAMA	-54.0	+22.1	-50.4	-16.3	-45.3	n.s.	-42.6

DESIGN REGION 6A

25% VARIATION IN SAAA,SAFA,SAMA,SAAB

PARAMETERS	P3DAMP	P2EXC	S2DAMP	S2EXC	F2	F2A	F2B
SAFA	-84.1	+ 9.2	-84.0	-96.4	-94.6	-11.4	-94.6
SAAA	+ 5.2	+74.5	+ 5.4	n.s.	n.s.	n.s.	n.s.
SAAB	n.s.	-10.8	n.s.	n.s.	n.s.	n.s.	n.s.
SAMA	n.s.	+ 5.4	n.s.	n.s.	n.s.	n.s.	n.s.

DESIGN REGION 6B

25% VARIATION IN SAAA,SAFA,SAMA,SAAB

PARAMETERS	P3DAMP	P2EXC	S2DAMP	S2EXC	F2	F2A	F2B
SAFA	-90.0	+10.6	-90.1	-93.9	-94.3	n.s.	-87.8
SAAA	n.s.	+80.2	n.s.	n.s.	n.s.	+49.1	- 4.1
SAAB	n.s.	- 4.1	n.s.	n.s.	n.s.	-45.0	+ 5.8
SAMA	+ 5.4	+ 4.9	+ 5.1	n.s.	n.s.	n.s.	n.s.

APPENDIX E

ISOCURVE DATA FOR FIGURES 8 AND 9

Parameters Defining an Approximate System Damping Characteristic of 1.00

SAAA/B	SAFA/MA	P3DAMP	P3EXC	S2DAMP	S2EXC
4	12.4	1.0049	-24.76	1.0231	32.88
6	13.5	1.0064	-26.38	1.0203	31.97
8	14.5	0.9960	-27.81	1.0070	31.07
10	15.3	0.9944	-29.06	1.0036	30.35
12	15.9	1.0037	-30.17	1.0118	29.80
18	17.5	0.9945	-33.12	1.0001	28.29
24	18.5	0.9999	-35.56	1.0039	27.28

Parameters Defining an Approximate System Damping Characteristic of 0.50

SAAA/B	SAFA/MA	P3DAMP	P3EXC	S2DAMP	S2EXC
4	17.0	0.4959	-26.11	0.5029	27.75
6	18.5	0.4948	-27.80	0.5001	27.08
8	19.7	0.5003	-29.26	0.5047	26.53
10	20.9	0.4958	-30.62	0.4995	25.94
12	21.8	0.5011	-31.83	0.5043	25.51
18	24.2	0.5009	-35.05	0.5031	24.34
24	26.0	0.5018	-32.82	0.5034	23.48

Parameters Defining an Approximate System Damping Characteristic of 0.25

SAAA/B	SAFA/MA	P3DAMP	P3EXC	S2DAMP	S2EXC
4	22.0	0.2515	-27.22	0.2544	24.39
6	23.9	0.2506	-28.96	0.2528	23.88
8	25.6	0.2500	-30.51	0.2517	23.40
10	27.1	0.2503	-31.92	0.2518	22.97
12	28.5	0.2496	-33.23	0.2509	22.56
18	32.0	0.2494	-36.72	0.2503	21.58
24	34.8	0.2503	-39.78	------	20.85

Parameters Defining an Approximate Secondary Excursion of 25%

SAAA/B	SAFA/MA	P3DAMP	P3EXC	S2DAMP	S2EXC
4	21.0	0.2868	-27.02	0.2902	24.95
6	21.7	0.3283	-28.52	0.3314	25.01
8	22.2	0.3700	-29.83	0.3729	25.03
10	22.5	0.4131	-30.99	0.4160	25.04
12	22.7	0.4544	-32.04	0.4572	25.03
18	22.8	0.5730	-34.69	0.5757	25.00
24	22.5	0.6815	-36.86	0.6839	24.99

Parameters Defining an Approximate Primary Excursion of 30%

SAAA/B	SAFA/MA	P3DAMP	P3EXC	S2DAMP	S2EXC
4	40.0	0.0251	-29.76	0.0253	18.76
6	30.0	0.1216	-29.98	0.1225	21.52
8	23.0	0.3369	-30.00	0.3395	24.61
10	18.5	0.6597	-30.01	0.6650	27.55
12	15.5	1.0568	-30.04	1.0656	30.19

Parameters Defining the System's Buffered Region

SAAA/B	SAFA/MA	P3DAMP	P3EXC	S2DAMP	S2EXC
6	17.8	0.5432	-27.62	0.5493	27.61
8	17.0	0.7062	-28.56	0.7131	28.59
10	16.3	0.8708	-29.37	0.8785	29.37
12	15.6	1.0432	-30.07	1.0518	30.09
18	13.85	1.5408	-31.75	1.5510	31.74
24	12.4	2.0112	-32.99	2.0225	33.01

APPENDIX F

DERIVATION OF A TRANSFER FUNCTION OF THE PRIMARY/SECONDARY CONTROL MODEL

The frequency analysis of the primary/secondary control model used in Chapter 5 is based on a transfer function between the primary system measure (primary inventory -- P3) and the input variable (unit sales rate -- PD) as a function of only the model parameters and the Laplace frequency variable, s. The transfer function is found by solving the set of Laplace transformed equations developed in Chapter 4 for the ratio P3:PD. These transformed equations are presented below for ready reference.

```
PB  = PBV*PBAP                         (2T)
PBV = S2/(1+PBVD*s)                    (4T)
P2  = (PB-PD)/s                        (7T)
PC  = PB/(1+PCXD*s)                   (10T)
P3  = (PC-PD)/s                       (12T)
PD  = PDNS/s                          (15T)
S2  = SB/s                            (17T)
S1  = (SA-SB)/s                       (20T)
SB  = SA/(1+SBXD*s)                   (23T)
SA  = (SAC-S2)/SAAA+(-S1)/SAAB        (27T)
SAC = SAD/SACP                        (29T)
SAD = SAE/(1+SADD*s)                  (31T)
SAE = SAF/SAFA+SAM/SAMA+SAH           (34T)
SAF = SAG-P3D                         (36T)
SAM = SAN-P2D                         (38T)
SAG = SAH*SAGA                        (40T)
SAN = SAH*PCXD                        (42T)
SAH = PD/(1+SAHD*s)                   (44T)
P3D = P3/(1+SAHD*s)                   (47T)
P2D = P2/(1+SAHD*s)                   (50T)
```

Here, the procedure for establishing the transfer function includes first solving the desired labor force, SAC, in terms of only the two primary flows, PC and PD. Substituting equation (31T) for the smoothed desired production start-up rate, SAD, into equation (29T) and using a special frequency variable constant (L1 = 1 + SADD*s) makes

SAC = SAE/SACP*L1 (52T)

Substituting equation (34T) for the manager's desired start-up rate, SAE, into (52T)

$$SAC = (1/SACP*L1)*(SAF/SAFA + SAM/SAMA + SAH) \tag{53T}$$

and substituting equations (36T) and (38T) for the perceived inventory error, SAF, and the perceived in process error,SAM, into the expression for SAC causes SAC to equal:

$$SAC = (1/SACP*L1)*[(SAG-P3D)/SAFA + (SAN-P2D)/SAMA + SAH] \tag{54T}$$

Substituting equations (40T) and (42T) for the desired inventory level, SAG, and the desired in process level, SAN, and regrouping by factoring the average shipment rate, SAH, leaves SAC as a function of three information delays.

$$\begin{aligned} SAC = (1/SACP*L1)*[SAH*(SAGA/SAFA &+ PCXD/SAMA + 1) \\ &- (P2D/SAMA + P3D/SAFA)] \end{aligned} \tag{55T}$$

The functions for the three information delays -- SAH, P2D, and P3D -- are all transformed incremental equations. Using a special frequency variable constant (L2 = 1 + SAHD*s) simplifies the form of SAC as equations (44T), (47T), and (50T) are substituted for the three information delays.

$$\begin{aligned} SAC = (1/SACP*L1)*[(PD/L2)*(SAGA/SAFA &+ PCXD/SAMA + 1) \\ &- (P2/SAMA + P3/SAFA)/L2] \end{aligned} \tag{56T}$$

Factoring the constants L2, SAFA, and SAMA on the right hand side of (56T) leaves

$$\begin{aligned} SAC = (1/SACP*SAFA*SAMA*L1*L2)*[(PD)*(&SAGA*SAMA \\ &+ PCXD*SAFA + SAFA*SAMA) \\ &- (P2*SAFA + P3*SAMA)] \end{aligned} \tag{57T}$$

and then simplifying the equation by using (C1 = SACP*SAFA*SAMA) and (C2 = SAGA*SAMA + PCXD*SAFA + SAFA*SAMA) for the appropriate constant strings, sets

$$SAC = (1/C1*L1*L2)*[PD*C2 - P2*SAFA - P3*SAMA] \tag{58T}$$

Substituting equations (7T) and (12T) for the primary accumulations P2 and P3, leaves SAC as a function of primary flows -- PB, PC, and PD.

$$SAC = (1/C1*L1*L2)*[PD*C2 - SAFA*(PB-PC)/s - SAMA*(PC-PD)/s] \quad (59T)$$

Transposing equation (10T) establishes PB in terms of PC

$$PB = PC*(1 + PCXD*s)$$

so that a factored and regrouped SAC equals:

$$SAC = (1/C1*L1*L2*s)*[PD*(C2*s + SAMA) - PC(SAFA + PCXD*SAFA*s - SAFA + SAMA)]$$

OR

$$SAC = (1/C1*L1*L2*s)*[PD*(C2*s + SAMA) - PC*(PCXD*SAFA*s + SAMA)] \quad (60T)$$

To complete the formulation of the transfer function it is necessary to solve for the production rate, PC, in terms of only the rate, PD. Again from equation (10T) and a special frequency variable constant (L3 = 1 + PCXD*s), PC can be written equal to PB/L3. Using equation (2T) for the start-up rate, PB, makes

$$PC = PBV*PBAP/L3 \quad (61T)$$

so that substituting equation (4T) for the smoothed labor force, PBV, and a special frequency variable constant (L4 = 1 + PBVD*s), sets PC equal to:

$$PC = S2*PBAP/L3*L4 \quad (62T)$$

From equation (17T) the secondary labor force, S2, equals SB/s, and from equation (23T) and special frequency variable constant (L5 = 1 + SBXD*s), SB equals SA/L5 and

$$S2 = SA/L5*s \quad (63T)$$

Using equation (27T) and substituting for the net personnel change rate, SA, S2 equals:

$$S2 = (1/L5*s)*[(SAC - S2)/SAAA + (-S1)/SAAB] \qquad (64T)$$

where S1 equals (SA-SB)/s from equation (20T) and from equation (17T) SB equals S2*s while from equation (63T) SA equals S2*L5*s, so that

$$S1 = [(S2*L5*s) - (S2*s)]/s$$

OR

$$\begin{aligned} S1 &= [S2*(1 + SBXD*s)*s - (S2*s)]/s \\ &= S2*SBXD*s \qquad (65T) \end{aligned}$$

Substituting equation (65T) for the employee processing delay, S1, in equation (64T), sets

$$S2 = (1/SAAA*SAAB*L5*s)*[(SAC-S2)*SAAB - S2*SBXD*SAAA*s] \qquad (66T)$$

Transposing and factoring S2

$$S2*SAAA*SAAB*L5*s = SAC*SAAB - S2*(SAAB + SBXD*SAAA*s)$$

$$S2[SAAA*SAAB*L5*s + SAAB + SBXD*SAAA*s] = SAC*SAAB$$

so that

$$S2=(SAC*SAAB)/[SAAA*s*(SAAB*L5 + SBXD) + SAAB] \qquad (67T)$$

Substituting equation (60T) for the desired labor force, SAC, into equation (67T) and then substituting equation (67T) for the labor force, S2, into (62T) to formulate PC as a function of PC and PD.

$$PC = \frac{PBAP*SAAB*[PD*(C2*s + SAMA) - PC(PCXD*SAFA*s + SAMA)]}{(C1*L1*L2*L3*L4*s)*[s*SAAA*(SAAB*L5 + SBXD) + SAAB]} \qquad (68T)$$

Transposing and factoring PC and PD sets PC as a function of PD.

$$PC = \frac{PBAP*SAAB*PD*(C2*s + SAMA)}{(C1*L1*L2*L3*L4*s)*[s*SAAA*(SAAB*L5 + SBXD) + SAAB] + PBAP*SAAB*(PCXD*SAFA*s+SAMA)} \qquad (69T)$$

Subtracting PD from both side and dividing both sides by the Laplace frequency variable, s, an equation for the primary inventory, P3, as a function of only the input variable, PD, can be written, because according to equation (12T) P3 equals (PC-PD)/s. Transposing the PD term and establishing a common denominator for the ratio P3:PD makes

$$\frac{P3}{PD} = \frac{\begin{array}{c}PBAP*SAAB*(C2*s + SAMA) \\ - (C1*L1*L2*L3*L4*s)*[s*SAAA*(SAAB*L5 + SBXD) + SAAB] \\ - PBAP*SAAB*(PCXD*SAFA*s+SAMA)\end{array}}{\begin{array}{c}(s*C1*L1*L2*L3*L4*s)*[s*SAAA*(SAAB*L5 + SBXD) + SAAB] \\ + s*PBAP*SAAB*(PCXD*SAFA*s+SAMA)\end{array}} \qquad (70T)$$

Simplifying the right hand side develops the final form of the transformation equation. Noting that all the special frequency variable constants include a Laplace frequency variable, s, the transformation equation for P3:PD is composed of a sixth order polynomial divided by a seventh order polynomial in s.

$$\frac{P3}{PD} = \frac{\begin{array}{c}PBAP*SAAB*(C2 - PCXD*SAFA) \\ - (C1*L1*L2*L3*L4*s)*[s*SAAA*(SAAB*L5 + SBXD) + SAAB]\end{array}}{\begin{array}{c}(C1*L1*L2*L3*L4*s)*[s*SAAA*(SAAB*L5 + SBXD) + SAAB] \\ + PBAP*SAAB*(PCXD*SAFA*s+SAMA)\end{array}} \qquad (71T)$$

This concludes the formulation of this particular transfer function of the primary/secondary control model. To solve the roots of the denominator (poles) and to calculate a scaled value for the gain of the transfer function it is necessary to expand the numerator and denominator terms of the function to calculate the coefficients of the sixth and seventh order polynomials. The numerator and denominator of this function were expanded and calculated using the DYNAMO compiler to multiply the model parameters that comprise each coefficient. Therefore, as the parameters are changed, the DYNAMO compiler calculates the altered values of the coefficients. The model equations for the calculation of the coefficients of the denominator of the transfer function are presented in Appendix G. The model equation form for the calculation of the transfer function as a function of the Laplace frequency variable, s, is presented in Apendix H.

APPENDIX G

COEFFICIENTS OF THE DENOMINATOR OF THE PRIMARY/SECONDARY MODEL TRANSFER FUNCTION

```
NOTE  THIS IS A MODEL TO SIMPLY CALCULATE THE COEFFICIENTS OF THE
NOTE  SEVENTH ORDER POLYNOMIAL IN THE DENOMINATOR OF THE
NOTE  TRANSFORMATION EQUATION OF S2/PD.
NOTE
N     B7=C1*E4*C4                                 SEVENTH ORDER COEFFICIENT
N     B6=C1*(E4*C3+E3*C4)                         SIXTH ORDER COEFFICIENT
N     B5=C1*(E4*SAAB+E3*C3+E2*C4)                 FIFTH ORDER COEFFICIENT
N     B4=C1*(E3*SAAB+E2*C3+E1*C4)                 FOURTH ORDER COEFFICIENT
N     B3=C1*(E2*SAAB+E1*C3+C4)                    THIRD ORDER COEFFICIENT
N     B2=C1*(E1*SAAB+C3)                          SECOND ORDER COEFFICIENT
N     B1=C1*SAAB+SAAB*PBAP*SAFA*PCXD              FIRST ORDER COEFFICIENT
N     B0=SAAB*PBAP*SAMA                           CONSTANT TERM
NOTE
NOTE  SUBSTITUTING IN THESE CONSTANT COMBINATIONS FOR E1,E2,E3,E4,C1,C3,C4.
NOTE
N     E1=PCXD+PBVD+SADD+SAHD
N     E2=(PCXD*PBVD)+(PCXD*SADD)+(PCXD*SAHD)+(PBVD*SADD)+(PBVD*SAHD)+
X      (SADD*SAHD)
N     E3=(PCXD*PBVD*SADD)+(PCXD*PBVD*SAHD)+(PCXD*SADD*SAHD)+
X      (PBVD*SADD*SAHD)
N     E4=PCXD*PBVD*SADD*SAHD
N     C1=SAFA*SAMA*SARP
N     C3=SAAA*(SAAB+SBXD)
N     C4=SAAA*SAAB*SBXD
NOTE
NOTE     MODEL CONSTANTS
NOTE
C     PBAP=5         UNITS/PERSON/WEEK            EMPLOYEE NORM PRODUCTIVITY ATT
N     PBVD=SAHD      WKS                          SMOOTH TIME OF LABOR FORCE
C     PCXD=12        WKS                          DESIRED PROCESS DELAY
C     SAAA=8         WKS                          SECONDARY ADJUSTMENT TIME
C     SAAB=8         WEEKS                        BACKLOG ADJUSTMENT TIME
N     SADD=SAHD      WEEKS                        PRESSURE SMOOTHING TIME
C     SAFA=20        WKS                          INVENTORY ADJUSTMENT TIME
C     SAHD=4         WEEKS                        AVG SHIP INFO DELAY TIME
C     SAMA=20        WKS                          ORDERS IN PROCESS ADJUST TIME
C     SARP=5         UNITS/PERSON/WEEK            MANAGERS NORM PRODUCTIVITY ATT
C     SBXD=12        WKS                          TRAINING & AUTHORIZATION DELAY
NOTE
OPT   PCL=14
OPT   R
PRINT B7,B6,B5,B4,B3,B2,B1,B0
SPEC  DT=1/LENGTH=1/PRTPER=1
RUN   DENOMS2
```

APPENDIX H

EQUATIONS FOR DYNAMO SIMULATION OF THE GAIN OF THE PRIMARY/SECONDARY MODEL TRANSFER FUNCTION

```
*       GAIN OF THE TRANSFER FUNCTION
NOTE
NOTE    THIS MODEL IS FOR THE CALCULATION OF THE SYSTEM
NOTE    GAIN WITH RESPECT TO A PARTICULAR INPUT FREQUENCY
NOTE
A      SCGAIN.K=GAIN.K*SCALE                      SCALES GAIN TO SHOW AMPLIFICATION
C      SCALE=0.1    WEEKS
A      GAIN.K=NUM.K/DEN.K                         GAIN
A      NUM.K=SQRT(NRS.K+NIS.K)                    SQ ROOT SUM OF SQUARES NUMER
A      NRS.K=(NR.K)*(NR.K)                        THE SQUARE OF THE REAL PARTS
A      NIS.K=(NI.K)*(NI.K)                        THE SQUARE OF THE IMAGINARY PARTS
A      NR.K=N0.K+N2.K+N4.K+N6.K                   THE SUM OF THE REAL PARTS
A      NI.K=N1.K+N3.K+N5.K                        THE SUM OF THE IMAGINARY PARTS
A      N0.K=((-B1)+(C2*PBAP*SAAB))                CONSTANT TERM
A      N1.K=(-B2)*TIME.K                          FIRST ORDER TERM
A      N2.K=(+B3)*TIME.K*TIME.K                   SECOND ORDER TERM
A      N3.K=(+B4)*EXP(3*LOGN(TIME.K))             THIRD ORDER TERM
A      N4.K=(-B5)*EXP(4*LOGN(TIME.K))             FOURTH ORDER TERM
A      N5.K=(-B6)*EXP(5*LOGN(TIME.K))             FIFTH ORDER TERM
A      N6.K=(+B7)*EXP(6*LOGN(TIME.K))             SIXTH ORDER TERM
A      DEN.K=SQRT(DRS.K+DIS.K)                    SQ ROOT SUM OF SQUARES DENOM
A      DRS.K=(DR.K)*(DR.K)                        THE SQUARE OF THE REAL PARTS
A      DIS.K=(DI.K)*(DI.K)                        THE SQUARE OF THE IMAGINARY PARTS
A      DR.K=D6.K+D4.K+D2.K+D0.K                   THE SUM OF THE REAL PARTS
A      DI.K=D7.K+D5.K+D3.K+D1.K                   THE SUM OF THE IMAGINARY PARTS
A      D0.K=B0                                    CONSTANT TERM
A      D1.K=B1*TIME.K                             FIRST ORDER TERM
A      D2.K=(-B2)*TIME.K*TIME.K                   SECOND ORDER TERM
A      D3.K=(-B3)*EXP(3*LOGN(TIME.K))             THIRD ORDER TERM
A      D4.K=(B4)*EXP(4*LOGN(TIME.K))              FOURTH ORDER TERM
A      D5.K=(B5)*EXP(5*LOGN(TIME.K))              FIFTH ORDER TERM
A      D6.K=(-B6)*EXP(6*LOGN(TIME.K))             SIXTH ORDER TERM
A      D7.K=(-B7)*EXP(7*LOGN(TIME.K))             SEVENTH ORDER TERM
N      TIME=0.004      WEEKS                 AVOID DIVIDING BY ZERO
NOTE
NOTE   CALCULATIONS OF DENOMINATOR COEFFICIENTS
NOTE
N      B7=C1*E4*C4                                SEVENTH ORDER COEFFICIENT
N      B6=C1*(E4*C3+E3*C4)                        SIXTH ORDER COEFFICIENT
N      B5=C1*(E4*SAAB+E3*C3+E2*C4)                FIFTH ORDER COEFFICIENT
N      B4=C1*(E3*SAAB+E2*C3+E1*C4)                FOURTH ORDER COEFFICIENT
N      B3=C1*(E2*SAAB+E1*C3+C4)                   THIRD ORDER COEFFICIENT
N      B2=C1*(E1*SAAB+C3)                         SECOND ORDER COEFFICIENT
N      B1=C1*SAAB+SAAB*PBAP*SAFA*PCXD             FIRST ORDER COEFFICIENT
N      B0=SAAB*PBAP*SAMA                          CONSTANT TERM
NOTE
NOTE   SUBSTITUTING IN THESE CONSTANT COMBINATIONS FOR E1,E2,E3,E4,C1,C3,C4.
NOTE
N      E1=PCXD+PBVD+SADD+SAHD
N      E2=(PCXD*PBVD)+(PCXD*SADD)+(PCXD*SAHD)+(PBVD*SADD)+(PBVD*SAHD)+
X       (SADD*SAHD)
N      E3=(PCXD*PBVD*SADD)+(PCXD*PBVD*SAHD)+(PCXD*SADD*SAHD)+
X       (PBVD*SADD*SAHD)
N      E4=PCXD*PBVD*SADD*SAHD
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```
N       C1=SAFA*SAMA*SARP
N       C2=SAGA*SAMA+SAFA*PCXD+SAFA*SAMA
N       C3=SAAA*(SAAB+SBXD)
N       C4=SAAA*SAAB*SBXD
NOTE
NOTE       MODEL CONSTANTS
NOTE
C       PBAP=5         UNITS/PERSON/WEEK        EMPLOYEE NORM PRODUCTIVITY ATT
N       PBVD=SAHD       WKS                     SMOOTH TIME OF LABOR FORCE
C       PCXD=12         WKS                     DESIRED PROCESS DELAY
C       SAAA=8          WKS                     SECONDARY ADJUSTMENT TIME
C       SAAB=8          WKS                     SEC BACKLOG ADJUSTMENT TIME
N       SADD=SAHD       WKS                     PRESSURE SMOOTHING TIME
C       SAFA=20         WKS                     INVENTORY ADJUSTMENT TIME
C       SAGA=10         WKS                     DES TURNOVER TIME OF INVENTORY
C       SAHD=4          WKS                     AVG SHIPMENT INFO DELAY TIME
C       SAMA=20         WKS                     PRIM BACKLOG ADJUSTMENT TIME
C       SBXD=12         WKS                     TRAINING $ AUTHORIZATION DELAY
C       SARP=5         UNITS/PERSON/WEEK        MANAGERS NORM PRODUCTIVITY ATT
NOTE
NOTE         OPTIONS AND MODEL SPECIFICATIONS
NOTE
OPT     MSV=140
OPT     D
NOTE
A       DT.K=DTXA+STEP(DTXS,DTXT)                 VARIABLE DT CALCULATION
A       LENGTH.K=LENA                             LENGTH CHANGE FOR RERUNS
A       PLTPER.K=PLTP+STEP(PLTS,PLTT)             VARIABLE PLTPER CALCULATION
C       DTXA=0.001      WEEK                      CALCULATION INTERVAL
C       DTXS=0         WEEKS                      CALCULATION INTERVAL STEP
C       DTXT=0         WEEKS                      TIME OF STEP IMPLEMENTATION
C       LENA=0.484      WEEKS                     TIME OF RUN TERMINATION
C       PLTP=0.004      WEEKS                     INTERVAL OF PLOTTING RESULTS
C       PLTS=0         WEEKS                      PLOTTING INTERVAL STEP
C       PLTT=0         WEEKS                      TIME OF STEP IMPLEMENTATION
SAVE    SCGAIN
PLOT    SCGAIN=G(0,4)
SPEC    SAVPER=0.004
RUN     SRNS36
```

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